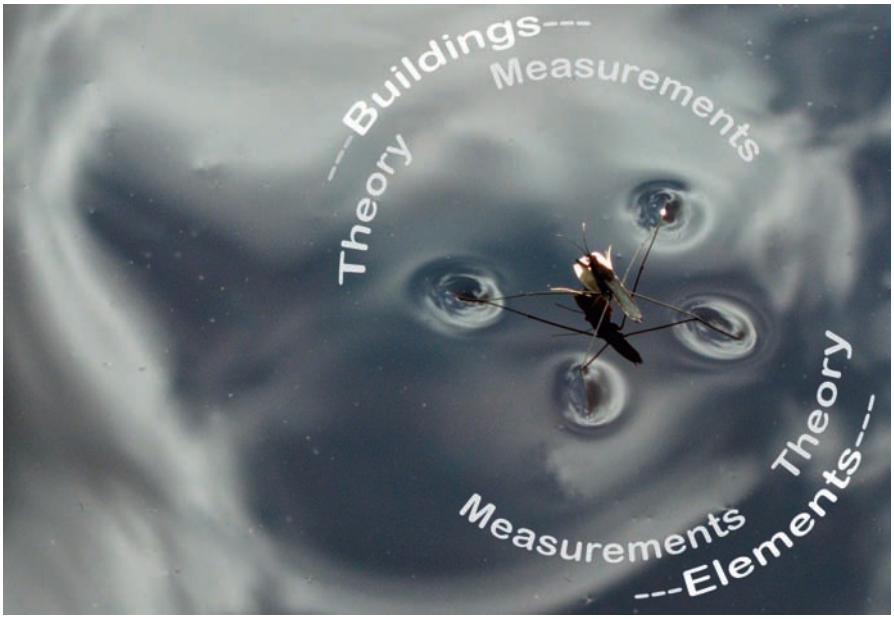
DOCTORAL THESIS

Managing uncertainty in building acoustics

- Comparisons of predictions using the EN 12354 standards to measurements



Christian Simmons

LULEÅ UNIVERSITY OF TECHNOLOGY

LULEÅ UNIVERSITY OF TECHNOLOGY

Managing uncertainty in building acoustics

- Comparisons of predictions using the EN 12354 standards to measurements

Christian Simmons

Luleå University of Technology
Department of Human Work Sciences
Division of Sound and Vibration

Printed by Universitetstryckeriet, Luleå 2009

ISSN: 1402-1544
ISBN 978-91-7439-028-5

Luleå 2009

www.ltu.se

Preface

The management of uncertainty in the field of building acoustics has become an increasingly important interest for me in the course of over 20 years of research, standardization and consultancy work[a]. In 2005, a conference on the management of uncertainty was held in LeMans, France. Experienced researchers met there to discuss the subject from many perspectives, from which I derived much inspiration.

In this thesis, I will discuss several aspects of uncertainty that I or other researchers have studied, with focus on practical applications of both measurement and calculation methods. The background and need for understanding uncertainties will be discussed in the Introduction.

An acoustician may improve the predicted performance of a building by means of some of the ideas suggested in this thesis. The main aim is to combine empirical knowledge (observations, measurements) from “the reality” with theoretical understanding and calculation models. The *Gerris lacustris* on the cover page illustrates this ‘cautious’ strategy – it cannot use only one or two legs to float on the surface of the water, it needs all its legs to stay safely on top. This picture helped me outline this thesis.

In the final chapter I will discuss fairly general aspects of the building process, which may be considered more of a management than a technical issue. However, it is important to include these aspects in the context of uncertainty, because preventing an unexpected sound performance of a building is not only a question of being familiar with the acoustical theory. It also involves a complex chain of decisions made during the building process and an increased understanding of this chain of decisions may help the industry to reduce overall uncertainty.

Acknowledgements

The studies that make up this thesis have been supported by Chalmers University of Technology, the National Council of Building Research (BFR), the National Board of Housing Building and Planning (Boverket), the Technical Research Institute of Sweden (SP), the Nordic Innovation Centre (NICe), the Development Fund of the Swedish Construction Industry (SBUF), the Swedish Concrete Federation, Skanska Sverige AB, WSP Group and Knauf Danogips GmbH. Luleå University of Technology has helped and encouraged me in course of writing the thesis. Many clients and colleagues have contributed to and supported the work, as did my beloved wife and wonderful children.

All support is hereby gratefully acknowledged.

[a] The author is a member of several standardization committees (SIS TK 197, CEN TC 126/WG 2 and ISO TC 43/SC 2/WG 18) and has been commissioned as an adviser to the National Board of Housing Building and Planning (Boverket).

Abstract

The present thesis summarizes the results of research on the uncertainty of standardized methods applied in the field of building acoustics, both in terms of calculations and measurements. Eight published papers are appended to the thesis. In order to provide the reader with a broader view, references to some relevant papers are also included.

The EN 12354 series of standards for calculation methods, published between 2000 and 2009 have facilitated the management of acoustic issues during the building process. To enable lean design of building structures, the uncertainty of the calculation methods (compared to measurement results) must be known, as the measurement results in finished buildings are typically used to prove the fulfillment of formal requirements. The standards facilitate a structured comparison of calculations (made during the design phase) with field measurement results. These comparisons have been used to estimate the combined uncertainty of the standardized methods and to derive safety margins that should be taken into account during design work (i.e. added to the calculated values).

There are several factors that complicate such comparisons, e.g. inaccurate building element input data, flaws in the interpretation of building drawings into calculation models, poor workmanship and uncertainty related to the field measurement methods. Some studies specifically address the uncertainty of the field measurement methods. Management issues that serve to reduce uncertainties pertaining to unclear definitions of requirements, poor building construction documentation and assignment of responsibility to be taken by the parties of the building process are discussed in a separate section.

Keywords: uncertainty, building acoustics, European standard, EN 12354, airborne sound insulation, impact sound, traffic noise, service equipment noise, structure-borne sound, sound absorption, reverberation time, calculations, field measurements.

Content

1 Introduction

1.1 Implementation of the EN 12354 standards in Sweden

There are several reasons why the EN 12354 standards play an important role for some parties involved in the Swedish building industry. The standards consist of six parts[1 2 3 4 5 6], which can be considered "the main links" in the world of building acoustics since they define a natural meeting point for developers, manufacturers, designers and contractors. This view is explained further in section 5.3.

The standards have also made it possible to apply a common approach to the prediction of the sound performance of buildings, where theoretical calculations can be combined with empirical data. Hence, uncertainty can be handled in a structured way, as discussed in this thesis.

The content of the appended papers and the structure of this thesis may be easier to understand if they are viewed in light of our building history and need for prediction tools. During the 1990's, the Swedish sound requirements and market situation changed considerably.

The frequency range of the sound insulation requirements was extended from 100-3150 Hz down to 50 Hz. In the case of sounds from service equipment, requirements were enforced in the range 31-200 Hz in addition to A-weighted sound pressure levels.

Building layouts changed considerably due to an amendment of the rules pertaining to subsidized building credits as well as changes in the market prerequisities for privately owned apartments. New apartments were thereafter designed with a wider variety of floor plans and construction methods, ranging from small inexpensive 'studios' to luxury 'exhibition spaces'. The prospective purchasers of expensive dwellings expected a better performance than the minimum requirements, and their residential houses were typically constructed with a 4-6 dB higher sound class.

Many new building products were introduced at this time. All of these changes made it difficult to use experience as the only basis for consultancy work (i.e. advicing architects and planners). Calculation tools and databases of sound insulation of building elements had to be developed and applied to predict the performance of new houses, as there were no comparable examples to relate to. Fortunately, new tools were developed and investigations of their feasibility for the Nordic countries conducted.

When the first five parts of the EN 12354 were adopted (in 2000 and 2003), it became necessary to demonstrate the accuracy of their calculation methods in practice, since in Sweden there was little experience of any comparable methods. The building construction products and methods used in the Nordic countries often differ from those employed in other European countries. The final part (-5) of the EN 12354 was adopted in 2009 and its three sections still remain to be tested under realistic conditions[b].

This thesis presents some examples and principles that may help consultants to communicate effectively with the commissioner in order to minimize overall uncertainty and improve

[b] The section 4.2 of part 5 describes a calculation model for the transmission of airborne sound from service equipment (e.g. a fan) through ducts etc. This model is reasonably similar to so called energetic models used by consultants in Sweden and other countries for many years. Thus it should be rather straight forward to implement the new calculation model in computer softwares etc. The section 4.3 describes a model for airborne sound transmission through building constructions which we already have some experiences of. The section 4.4 treats the prediction of structure-borne sound transmission which has often been regarded as a hassle by the consultants. Structure-borne sound may now be somewhat easier to handle, as there are new methods for determining the source strengths of many types of building service equipment. However, the propagation of structure-borne sound is difficult to predict as it often involves transmission across several junctions between heavy building elements and hence conversion between wave types. This is an appropriate field for future research. C.f. section 3.6.1.

the understanding of variations in sound and sound insulation in buildings[c]. The main aim is to apply several tools in a sequence and to improve a theoretical prediction by means of comparison with a population of measurements (structured feedback). This procedure combines empirical knowledge (observations, measurements) from "the reality" with theoretical understanding (calculation models as implemented in available computer software). It is well adapted to the demands and tolerances of the Swedish sound requirements.

The data and analyses in the studies referred to in this thesis are derived from short applied projects that took place over an extended period 1986-2009. These projects focused on the implementation of new methods etc and were carried out with very limited budgets, which did not leave any room for extensive theoretical comparisons, literature reviews etc that would have been of scientific interest. Greater resources would have allowed more data to be collected etc, but the scope of each project was too restricted for this. For instance, each building site should have been analyzed to find out which transmission paths dominated the overall sound reduction index and how this differed from the theoretical estimation according to the EN 12354. Hence, there are "missing parts" in this thesis that would have been desirable to include, and its structure is somewhat different to what may be regarded as 'typical' at a university of technology. Where appropriate, references are given to papers by other researchers, in order to fill in some missing parts and to give the reader a broader perspective. Some issues where future research would be of interest are also pointed out.

This thesis does not contain detailed information about the calculation models in the EN 12354 standards. An example of a typical structure is provided in clause 2.1. However, in the future, results presented in this thesis may be valuable in the process of improving the accuracy of some of the theoretical models in EN 12354, e.g. for the airborne and impact sound insulation of heavy building structures. Research is currently being conducted by several institutes to extend the EN 12354 models in terms of airborne and impact sound insulation of lightweight building elements, but this issue is not addressed by the present thesis.

The main part of this thesis is probably of greatest interest to acousticians and building designers. However, unexpected sound performance of a building is not only a matter of acoustical technology. The chain of decisions made in the building process is complex and an improved understanding of its structure may help the industry reduce overall uncertainty. The introduction of the EN 12354 series of prediction standards in 2000 made it possible to describe a scheme for shared responsibility among all parties in the building process, supported by the ISO 140-series of measurement standards. Some examples of this broad perspective are discussed in section 5.3.

1.2 History of the development of the EN 12354

In 1989 the European standardization committee for building acoustics (CEN/TC126) proposed to the European Commission that it would develop calculation tools to link the performance of a building (*the works*) to that of its building products and materials. The need for such tools and the background of this initiative is explained by Gerretsen in Acta Acustica in 1994[7]. CEN was then mandated by the Commission to develop these tools in the EN 12354 series of standards. The first four parts (on sound insulation) were adopted by CEN in 2000. Part 6 (on room acoustics) was adopted in 2003 and part 5 (on sound from service equipments) in 2009[b].

The EN 12354 standards support the intended purpose of the CPD (the Construction Product Directive 89/106/EEC). The CPD requires products on the common market to be de-

[c] An example: a consultant is commissioned by a client to propose affordable building constructions that fulfil the requirements. Preferably, these constructions should be chosen at an acceptable risk of failure. For example, if interior traffic noise must not exceed 30 dB in more than one out of ten apartments (or by more than 2 dB), the consultant should apply statistical analyses to determine appropriate constructions. However, there is rarely sufficient time or data at hand to describe all relevant circumstances, nor to make profound scientific analyses. The commissioner is not always aware of the inherent difficulties and may not understand the conditional statements made by his/her building acoustic consultant about the expected performance of the building. There are many sources of uncertainty in this field and it is often not possible to "warrant" a certain performance without taking a risk or imposing additional costs for excessive constructions. C.f. section 2.3.

signed for buildings that fulfill so called “essential requirements”. Buildings should also fulfill any other requirement set by the local authorities, commissioners or contractors.

However, even if the acoustic performance of products can be determined by means of standardized measurement methods (or other methods, c.f. section 2.3), the data from such tests are not sufficient to prove compliance with the local building regulations that typically refer to the conditions of the building. To assess whether a product can help to meet these requirements, the acoustic performances of products needs to be translated into the acoustic performance of the building, taking the influence of other building products and boundary conditions into account. This is what the EN 12354 standards are designed for.

Using these standards, several combinations of products can be tested by the designer to find one or several feasible combinations. This possibility facilitates the use of functional requirements on building performance (e.g. sound insulation between rooms) compared to construction requirements, e.g. **“**minimum dimensions”, “authorized solutions” and similar (that are typically based on empirical experiences). This is discussed further in section 5.1.

The EN 12354 also facilitates the free trade of products. These effects appear particularly important when new products; materials or architectural solutions are suggested during the building process, where construction/dimension types of requirements are conservative by nature. Free trade is of particular importance to the Swedish building industry, since the domestic market is small and both products and turn-key building projects are imported and exported.

2 Calculations according to EN 12354

2.1 Structure of a calculation model (part 1)

The EN 12354 standards consist of several parts that cover the most important acoustic properties of buildings: airborne and impact sound transmission between rooms (parts 1 and 2), sound transmission from or to the outside (parts 3, 4), airborne sounds and structure-borne sounds from service equipment (part 5) as well as reverberation control of rooms (part 6).

The calculation methods are described by each of the EN 12354 standards. An overview of the formulas used in parts 1-4 was presented in 1994 by the convener of the CEN/TC 126/WG 2 in a comprehensive article in Acta Acustica[7]. Part 4 that treats sound transmission from inside a building to the exterior has not been applied by the present author and will not be discussed further in this thesis. Parts 5 and 6 are discussed later in this thesis.

The calculation model for airborne sound insulation between rooms (part 1) serves as an example of the structure of the standards. The model is established in several steps:

- The direct airborne sound reduction index *R* expresses the direct sound transmission through a separating element (partition) between two rooms (e.g. a wall or a floor), as measured in a laboratory with suppressed flanking transmission in accordance with ISO 140-3. This quantity *R* is then corrected in the consecutive steps.
- Small elements (components) may be inserted in the partition, such as doors, windows and ducts, and the sound insulation of the partition is corrected for their additional transmissions.
- The flanking sound reduction indices of 4 separate structural paths are added, e.g. by 2 floors and 2 walls in the horizontal direction or 4 walls in the vertical direction. Flanking transmission may also be caused by extraneous systems, e.g. ducts, plenums (above ceilings), corridors etc, provided their flanking sound reduction indices are provided. The figure 1 from the standard illustrates the transmission paths:

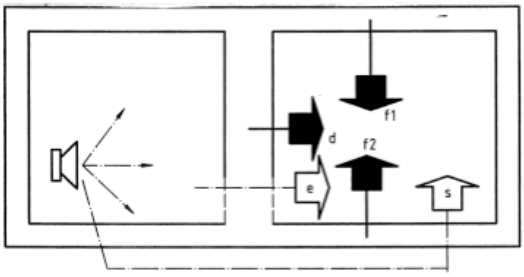


Figure 1. Illustration of the different contributions to the total sound transmission to a room: d – radiated directly from the separating element, f1 and f2 – radiated from flanking elements, e- radiated from components mounted in the separating element, s- indirect transmission. From the first part of the EN 12354 standard[1].

- The sound reduction of additional layers, e.g. wall linings, suspended ceilings and floating floors, may be added to the sound reduction index of the elements they are attached to, provided the latter are heavyweight elements.
- The type of junction between the connected structures determine the vibration reduction index K_{ij} of each junction, which helps reduce the flanking transmission. The standard includes a variety of types of junction and formulas to calculate the vibration reduction index from the structural properties of the connected elements, provided these are homogenous. For complex junctions, the K_{ij} must be determined by the user of the standard, e.g. from dedicated measurements.
- The vibration reduction index of the junctions also alters the structural reverberation time (i.e. the loss factor) of the heavy elements, compared to the laboratory situation[d]. This can be taken into account by the detailed calculation model.
- Lightweight elements are described by their direct sound insulations without changing their loss factors. The effect of any additional layers should be included with the data of the element itself. The radiation efficiency from flanking lightweight structures is less than from heavyweight structures (below the coincidence frequency), which may be corrected for in cases where its *R* value is taken from a laboratory test (of direct transmission) to describe its flanking sound insulation[e].

All measurements and calculations of airborne and impact sound transmission referred to in this thesis are made in the 50-3150 Hz third-octave bands in accordance with the detailed EN 12354 models of parts 1 and 2. The calculations are made for buildings with concrete slabs only, where the walls are made of concrete or lightweight materials (e.g. plasterboards). The main reason for this restriction is that the calculation models in the EN 12354 have not yet been adapted to buildings constructed with only lightweight structures (e.g. timber joist floors, walls) and junctions between these elements[f].

---

[d] For many typical buildings in Sweden, the loss factor of heavy elements may vary considerably because the number of heavy elements connected to the partition typically varies from 1-3. There are even cases where there are no heavy flanking elements at all (e.g. small offices with lightweight walls on a large concrete slab) or 4 heavy elements (e.g. walls of a small bedroom between an elevator shaft and the façade element). Thus, it is important to correct for the loss factor. However, more field data and comparisons to theoretical estimations would be valuable.

[e] The reason for this difference is that in the laboratory setup, both forced and free vibrations determine its sound insulation, whereas in the flanking situation, only free vibrations radiate sound. Below the coincidence frequency, the radiation efficiency is less than 100%. A typical value of 10% may be applied for plasterboard walls with wooden studs or other stiffening structures attached to the plasterboards, i.e. the flanking insulation is 10 dB higher.

[f] Some ideas for future revisions of the EN 12354 have been proposed (e.g. by Nightingale, Schoenfeld and others), but it is expected to require considerable efforts to develop the models, find relevant input data and assess the calculation accuracy with comparisons to field measurements. Transmission of sound through complex junctions, particularly at low frequencies, constitutes demanding challenges for the researchers involved in the work[f]. Some measured data and experiences of light weight floors are discussed in a short paper by the present author[f].

2.2 Adaptation of "shoe-box" calculation models to real building layouts

The designer is assumed to make some 'best-choices' when a shoebox model (of EN 12354-1 and 2) is specified in order to resemble the real layout of the rooms in a building. These choices should be based on both theoretical understanding and practical experience of building constructions, since each choice influences the uncertainty of the calculation result:

- Room geometries (i.e. walls and floors of the sending and receiving rooms should be exposed to approximately the same amount of incident sound as in the real building.
- Partition area and receiving room volume should be the same as in the building (and will be relevant in the case of field measurements in the building).
- Data of sound insulation and material parameters should be relevant for each element and additional layer used in the real building.
- Types of junction that resembles each type of connection between these elements.
- Junctions between prefabricated concrete elements need some consideration in terms of which model to use for the calculation of the vibration reduction index (K_{ij}). For the time being, the model for rigid junctions has often been applied as the best guess, but it should be examined thoroughly whether this is a valid assumption. The quality of the workmanship may influence whether airborne sound leaks through cracks and whether the elements are rigidly attached to each other. In cases of poor workmanship, flanking transmission could be larger than estimated by the calculation model.
- Light weight walls and façades are assumed to increase the loss factor of continuous heavy elements connected to them, but which loss factor is reasonable to insert in the calculation still needs to be examined.[d]
- In the present edition, there is no calculation model for junctions between heavy slabs and heavy double walls (masonry or elements), but there are some suggestions for extending the standard in the future as well as some laboratory studies on such constructions.
- Influence of workmanship may be modelled and corrected for in a separate risk analysis, e.g. for the influence of air leakage through cracks, for structure-borne sound through too weak connections as well as too stiff connections that are not supposed to be present.

To the present author's knowledge, no systematic analyses have been conducted on the impact of these choices (made by the designer) on the accuracy of the calculation results. A very limited study on the effect of choices was performed within a Nordtest project in 2003 (c.f. sections 4.1.1 and 4.1.2[g]).

2.3 Different sources of input data

The acoustic performance of building elements and the junctions between them are needed as input to the EN 12354 calculation models in which sound insulation between rooms or reverberation time inside a room are estimated. Data for the sound sources are also required for the estimation of the sound pressure level in rooms.

Input data for the elements (walls, slabs, flooring, windows etc.) may be obtained by several methods. The most common are measurements in the laboratory and in buildings as well as theoretical calculations or considerations on the basis of experience.

The CEN technical committee on acoustics (TC 126) has issued a technical report with guidelines on how to declare the acoustical properties of products[8]. The guidelines are intended to assist product technical committees (TC's) to specify acoustical requirements when

[g] Short courses on the use of the standards for acoustic consultants and structural engineers have indicated that they tend to make rather similar choices provided they have some experience of building acoustics. Inexperienced users of an EN 12354 calculation software tend to define a variety of room models that increase the uncertainty.

formulating product standards. The report assigns responsibility for the declaration of a product's acoustic properties to its manufacturer[h].

There are advantages as well as disadvantages with all types of source, and consultants may sometimes express rather critical experiences of (or attitudes to) each of the following:

- "*Laboratory measurements*" – they only reflect the real performance of 1 sample product in 1 sample laboratory under ideal circumstances. In order for them to be useful, there must be a series of tests, under non-idealized conditions, performed in several laboratories. At the very least, one should consider general results from round robin tests and the reproducibility of such measurements[i].
- "*Field measurements*" (also referred to as measurements *in situ*, in the building or in the field) – they reflect the performance of an assembly of products under realistic yet more or less unknown circumstances. Hence their performance may depend on workmanship and they may differ between buildings. The measurement uncertainty is larger in the field than in the laboratory because of non-ideal sound fields and higher background noise. As an example, the Robust Details[84] system requires 30 field measurements to document the performance of a specific product or construction.
- "*Theoretical calculations*" – can only estimate the performance of a product with assumed properties, their accuracy being limited by the theoretical model and underlying assumptions.

Sometimes the last mentioned source is the only feasible one, e.g. when no measured data are available. It may also be the preferred method for characterizing some products, e.g. monolithic structures (concrete slabs and walls), that interact with the structure of the laboratory and hence yield results that depend on the test condtitions[7]. The TR 15226 guidelines[h] recommend the annex B in EN 12354-1 for the declaration of the properties of such elements[j].

Theoretical calculations are the most widely used source of data for the vibration reduction index, although some applications have been reported where this index has been measured (e.g. for masonry walls and glazed façade elements with aluminum profiles).

Wittstock carried out a thorough investigation of the factors that contributes to the global uncertainty of measured airborne sound reduction and its weighted single numbers[9]. This is referred to as an *uncertainty budget*. He also compiled an overview of round robin tests[10], where different types of element were circulated for measurements in European laboratories. Such round robins have been made for limestone walls, lightweight walls (c.f. references *12*, *13* and *24* of Wittstocks paper in ActaAcustica[9]) and windows[11].

The figures (2, 3 and 4) from these publications illustrate the scatter of results obtained in the round robin tests mentioned[11 12 13]. As illustrated by these Figures, the scatter of results reported from these round robin laboratory tests was surprisingly large. Olesen commented upon the results for a window that was circulated among 5 laboratories:

"*A considerable deviation between the laboratories is seen in the frequency range 50 Hz to 100 Hz. It is remarkable that the difference between highest and lowest result at 50 Hz is more than 25 dB*"

Efforts have since been made to improve the measurement standards with respect to laboratory conditions and mounting instructions[k].

---

[h] CEN TC 126/WG 5 proposal prCEN/TR 15226:2005 (E) specifies the technical requirements related to acoustics for a product standard, European Technical Approval Guidelines (ETAG) or European Technical Approval (ETA) for a specific building product or equipment, or a family of building products or equipment. In particular, it provides advice on how to formulate requirements in response to the mandated characteristics (e.g. acoustics) under the Construction Products Directive. It also recommends that product TC committees contact WG 5 for assistance.

[i] Reproducibility, repeatability and accuracy of measurements are described in ISO 5725 and ISO 140-2.

[j] Prefabricated concrete elements, e.g. hollowcore slabs, need to be modelled differently with respect to impact sound. This is discussed later in this thesis.

[k] e.g. ISO 140-3:1995/Amd 1:2004, Installation guidelines for lightweight twin leaf partitions. For heavy partitions, several suggestions have been made (c.f. Gerretsen[7]) but no change has been implemented in the ISO 140-series.

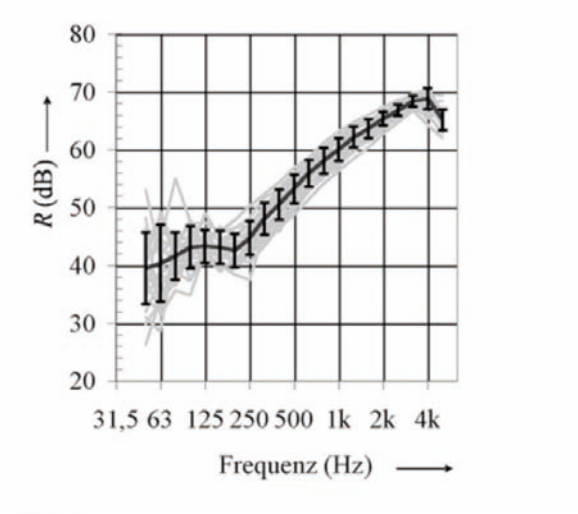


Figure 2. Sound reduction index of limestone walls. Black; average and standard deviation. Grey; individual measurement results from 20 different laboratories. From ref. 10.

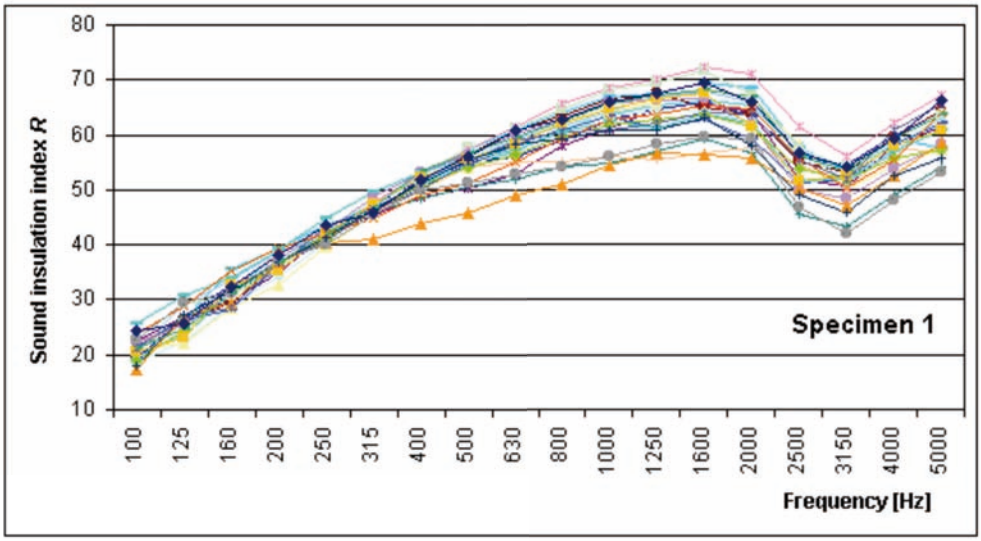


Figure 3. Sound reduction index of walls with one plaster board attached to each side of metal studs and rails. 24 laboratories. From ref. 13.

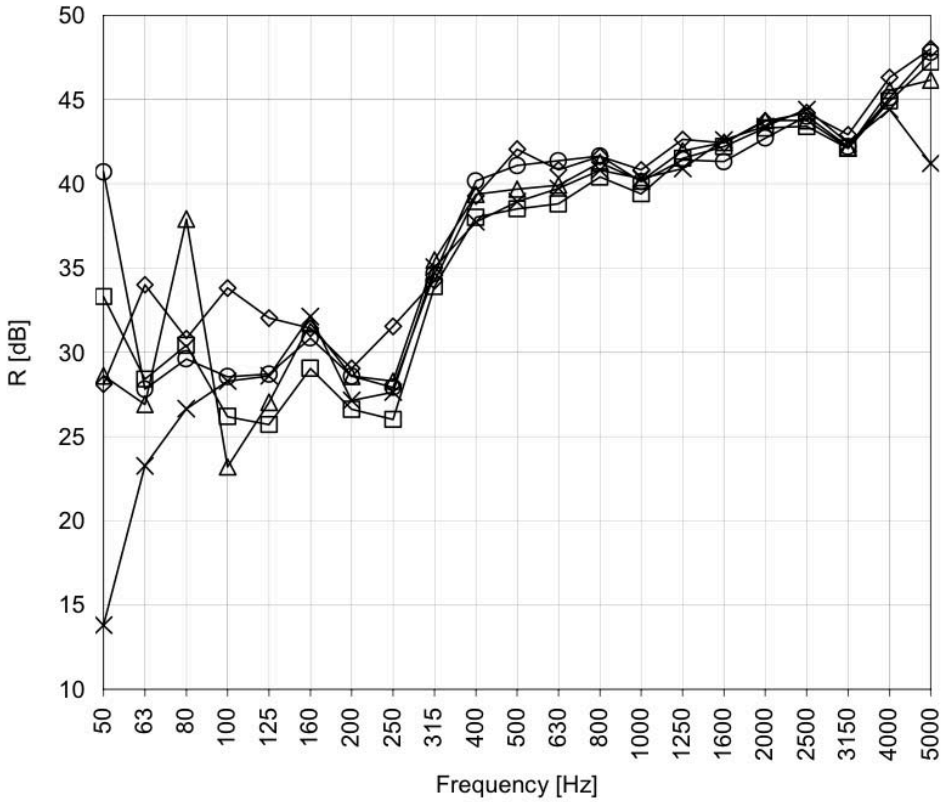


Figure 4. Laboratory measurements of sound insulation of a window in accordance with ISO 140-3 in the frequency range 50 Hz to 160 Hz. Five Nordic laboratories participated in this comparison. From Olesen[11]

A few round robins aimed to test the reproducibility of the methods for field measurements under stable conditions (i.e. at the same measurement sites), which will be discussed in chapter 4. A working draft of a revised ISO 140-2 standard[14] is based on results from the above mentioned round robin tests[I].

There is general agreement within the standardization bodies to address uncertainty issues in all new measurement standards. Brinkmann described this policy in a speech given at a conference on uncertainty in LeMans, France in 2005[15]:

"*The international Standard ISO/IEC 17025 from 1999 on the competence of laboratories requires that calibration and testing laboratories shall have and shall apply procedures for estimating the uncertainty of their measurement results. Laboratories following closely international or regional standards in their measurements, on the other hand, expect that these standards provide valid information and guidance for the evaluation of uncertainty. This situation gave the main background for ISO/TC 43 "Acoustics" and its SC 1 "Noise" to agree, at their plenary meetings in 2003, on a strategy on how to implement this request in each newly developed or revised standard related to any kind of acoustic measurement. It was basically concluded to refer all future uncertainty considerations to the GUM. However, in cases*

[I] This draft will hopefully result in an approved third edition of this standard that makes it more practical to assess the uncertainty in the individual application (compared to the current edition of this standard from 1991). The draft is focused on general aspects and airborne sound insulation, but it would be valuable to fill in relevant data for some other quantities of the ISO 140-series as well, e.g. impact sound insulation, traffic sound insulation etc.

where existing knowledge is not yet sufficient to apply the GUM in each detail, certain deviations are allowed in order not to cause unjustifiable delays in ongoing standardization projects."

The GUM mentioned is the ISO Guide to the expression of Uncertainty in Measurement[16]. The association for the accreditation of technical laboratories in the European member states (EAL) has increasingly stressed the need for this work to be performed by the standardization committees within CEN. The accredited laboratories are urged to implement adequate routines for the estimation and declaration of uncertainty in their test reports.

However, this has been more difficult to achieve within the field of building acoustics than first anticipated. The draft ISO/WD 140-2[14] recommends repetitive round robin tests as the primary tool for the assessment of the uncertainty of each test method and its practical implementation at the laboratory (i.e. its routines). Wittstock examined the relation between the uncertainty of the weighted airborne sound reduction index and the uncertainty of the indices in third octave bands and concluded that it was very complicated due to some cross-correlation between the frequency band values[17]. The uncertainty of the weighted number is overestimated when the uncertainty of the third octave band values are added without correction for the cross-correlation.

It should be noted that in spite of the difficulties mentioned in the draft ISO/WD 140-2[14], the GUM procedure can still be used to scrutinize measurement routines and find sensitive parts therein, e.g. the influence of spatial averaging on the average sound pressure level or reverberation time within a room. If there is a need to shorten the measurement time, an uncertainty budget helps find out which terms influence the final result most and which could be simplified. For instance, it is not uncommon that only one loudspeaker position is used in airborne sound reductions index measurements. Whether this is a reasonable simplification or not could be studied. Olesen studied several complications in the application of the standards for measurements in the field[18] and made recommendations on procedures for difficult cases, which were later summarized in ISO 140-14.

The instrumentations in the laboratories must be calibrated with traceability to national and international references, but it could be noted that the contribution of instrumentation uncertainty is often low compared to other factors. The uncertainty of input data is discussed further in section 3.1.

2.4 Design goals

2.4.1 Design goals, tolerances of requirements and safety margins

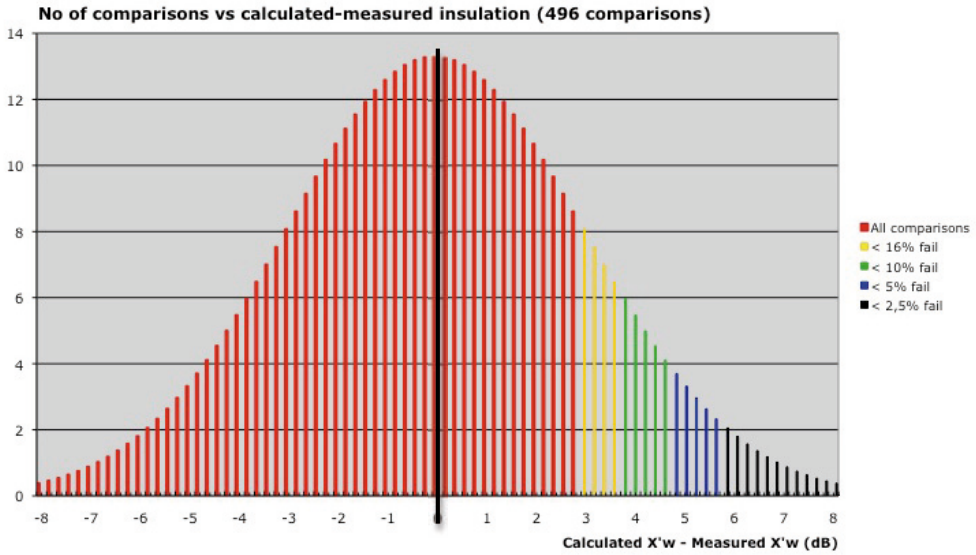
The most widely used sound requirements in Sweden are described by two national sound classification standards[19, 20] published by the Swedish Standards Institute (SIS). The National Board of Housing, Building and Planning (Boverket) refers to these standards in the building codes[21] BBR[m].

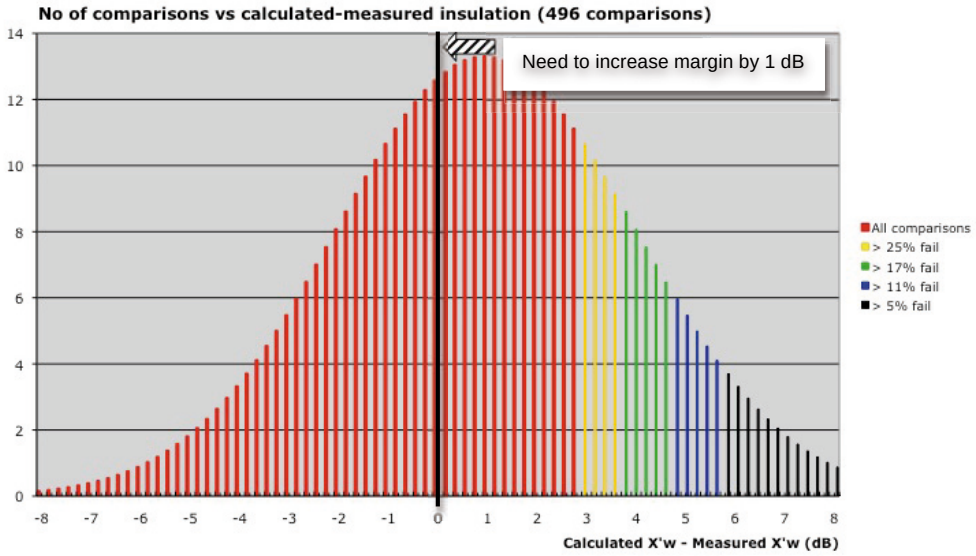
The SS 25267 and SS 25268 standards include tolerances that must be observed when sound insulations, sound pressure levels or reverberation times are verified by measurements in the building. SS 25267 and SS 25268 state that the results of field measurements must meet each type of requirement on the average within each dwelling or commercial premise. The maximum unfavourable deviations from the requirements are

- 1 dB for the single weighted numbers of sound reduction (ISO 717, 100-3150 Hz)
- 2 dB when spectrum adaptation terms for low frequencies (50-3150 Hz) are included
- 2 dB for service equipment sound pressure levels in third octave bands 31-200 Hz.
- 0,1 seconds for the reverberation time in octave bands 250-4000 Hz, 0,2 s in the 125 Hz octave band (described in section 3.7)

[m] Typically, the standards are used by local authorities to state formal requirements, but they may make specific exceptions that deviate from the standards. Some large developers (e.g hospitals) may add specific requirements that should be observed as well. In the context of the thesis, the standards are referred to as "the requirements".

The principal design goal is to consecutively fulfill two types of requirements; average as well as maximum deviations. The designer may need to correct calculation results with respect to *systematic* variations between calculated values and several field measurements, as well as to keep a margin for *unexpected (random) variations*. Figures 5a and 5b illustrate the effect of both types of variation. There are no systematic differences in figure 5a, but the measured value may deviate from the calculated value in an unpredictable manner. If the calculated value is one standard deviation (3 dB in this example) above the requirement, the measured value might have a 16% risk of failure, i.e. 84% of all measurements are likely to pass. The upper limit for sound pressure levels must not be passed and the margin should be applied with a reversed sign. (*…continues below*)





Figures 5a and 5b. Safety margins. The graphs depict the 'occurrence' of differences between weighted calculated and measured sound insulations, based on 496 fictive cases that follow a normal distribution (Gaussian). a) with random variations only (upper). b) with 1 dB systematic 'overestimation' added to the same random variations (lower). 3 dB standard deviation is applied in both examples, with coverage factors of 1,0;1,28; 1,6 and 1,96. Risks of failure (measured value < calculated value incl. safety margin) are indicated to the right.

(*contin.)* In the bottom figure (5b), there is a systematic difference where the calculated value overestimates the insulation by 1 dB compared to average measurements. This systematic difference should also be corrected for, i.e. the margin should be increased by 1 dB. If the same 3 dB margin were applied, the risk of failure would increase from 16 to 25%.

The field measurements should preferably be taken in furnished rooms in buildings with documented constructions under well-controlled quality workmanship. This would yield a long-term average performance of the products. Calculations of the performance of buildings with these product data should agree with the measured average performance in the field. However, unexpected and unfavorable variations from the calculated value (*scatter*) endanger compliance with the tolerances of the requirements. Such variations may be due to several factors, e.g. the quality of workmanship. The design of the product may be improved to reduce its sensitivity to errors in workmanship, e.g. by encapsulating elastic mounts etc.

The uncertainty of a field measurement is determined by several sources of error, e.g. time and spatial averaging of sound pressure levels, reverberation time measurements (slope of sound decays), background noise and equipment sensitivity errors. These problems are discussed (briefly) later in this thesis.

Thus during the design work, both systematic and random variations must be considered by means of appropriate safety margins, preferably based on experience of the actual type of building products[n]. Discussions about and examples of adaptation of input data for building elements that cannot be tested in laboratories are presented in section 3.

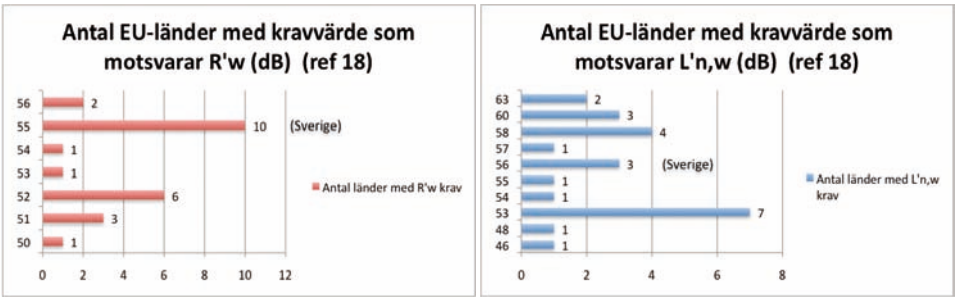
2.4.2 Single number values and subjective annoyance

Another field of interest, where it may be useful to make more research in the future, concerns the use of weighted single number values (e.g. ISO 717) and their relation to subjective reactions to sounds (annoyance of the part of the residents). Rasmussen provided an overview of sound requirements in the European member states[22]. In the first edition of SS 25267 in 1996, the previously used parameter R'_w was replaced by $R'_w + C_{50\text{-}3150}$ and in the third edition by $D_{nT,w}+C_{50\text{-}3150}$. $L'_{n,w}$ was then complemented by $L'_{nT,w}+C_{I,50\text{-}2500}$. The purpose of these changes was to improve the correlation with subjective performance (for impact sound based on studies e.g. by Hagberg[23]). The SS 25267 also states maximum C-weighted sound pressure levels and third octave band values (31-200 Hz) to prevent disturbing sounds from e.g. heat pumps.

However, there are indications that even these changes have not been sufficient to prevent all types of sounds from being judged acceptable based on measurements and criteria contained in the SS 25267. This should be investigated further, e.g. with respect to very low frequency impact sound through timber joist floors, vibrations of the floor and supporting walls as well as tonal/impulsive sounds from heat pumps and similar equipments.

Airborne sounds from neighbors are not well described; the current requirements merely comprise long-term empirical knowledge of what is needed. Rasmussens comparison of the requirements in 24 European member states[22] revealed that there are no major differences when the various types of requirement are "converted" into "equivalent" single number values (R'_w and $L'_{n,w}$). Figures 6a and 6b[85] summarize these requirements.

[n] A sample measurement taken in a completed building is often considered "the true performance". This may be adequate in an individual case, e.g. for a buyer of an apartment, but it should not be used to "tune" input data.



Figures 6a and 6b. (figures 4.4 in the handbook[85]). Summary of the requirements of 24 member states. Left (a); number of EU-states applying an equivalent R'_w-value. Right (b); number of EU-states applying an equivalent $L'_{n,w}$-value. Rasmussen converted the requirements based on spectrum adaptation terms or volume restrictions to the equivalent R'w ($L'_{n,w}$) values without the adaptation terms (c.f. ref.[22]).

The fact that many countries use similar levels in their requirements does not imply that they are optimal with respect to modern life and the expectations of people buying and living in apartments. Hagberg, Bradley, Vorländer and others have suggested new principles for evaluation criteria[o].

The standardized tapping machine (ISO 140-7) has been questioned with respect to lightweight floors, in particular by Japanese researchers (Tachibana) and others. Pyoung *et al* examined psycho-acoustical characteristics of impact ball sounds on concrete floors[24]. It would be advantageous to investigate these issues further, as they affect the perceived quality and the competitiveness of different building systems.

3 Input data

3.1 Improving accuracy by structured feedback

As discussed in section 2.3, there are no methods that can be used to *exactly* determine the performance of elements and junctions – all methods suffer from various types of inaccuracies. It may be intuitively correct to assume that sample measurements in the laboratory or field[n)] are the "true values" and to adapt a calculation model or the input data to fit these measurements. However, several experiences and considerations make this assumption less attractive and a more feasible approach is suggested in this section, together with some examples of application.

Erroneous measurements should be removed from data that will be compared with calculations, whether these are due to measurement errors (e.g. background noise), bad workmanship (e.g. air leakage) or merely a poor documentation of the building constructions (imprecise references). Such measurements may still be analyzed statistically, since they reflect realistic experiences from the field. The comparisons may as well highlight needs for improving measurement routines, workmanship and the description of the constructions. Changes of the calculation model or its input data should be the next step, if needed.

In the present author's experience, unexpected differences between calculated and measured values can be caused by errors in the description of the building element. These mistakes are often detected by comparison between calculations and measurements, e.g. by

[o] A new research initiative has been taken by Rasmussen et al, where European scientists from more than 22 member states will meet in a EU based COST-activity to coordinate research on these issues.

comparing the resonant (fundamental and coincidence) frequencies. Considerable differences in the sound insulation at low frequencies may often be explained by erroneous weight data[p].

Calculations of the performance of elements are sometimes regarded as the "the best guess", but they may (as mentioned in section 2.3) be closer to the long term average performance to which they should be compared than sample measurements. This apparent conflict of views is sometimes expressed (*with a twinkle in the eye*) as

- *Everybody believes in measurements, except those who make them*
- *Nobody believes in calculations, except those who make them*

Calculation models may be improved after systematic comparisons with large populations of measurements, including a variety of constructions, measurement locations and measurement operators. If errors tend to be related to one source of input data for a certain construction (element) but are not observed for other sources, it is more relevant to study the specific construction and its input data (rather than changes of the calculation model). An illustration of this procedure is presented in Figure 7:

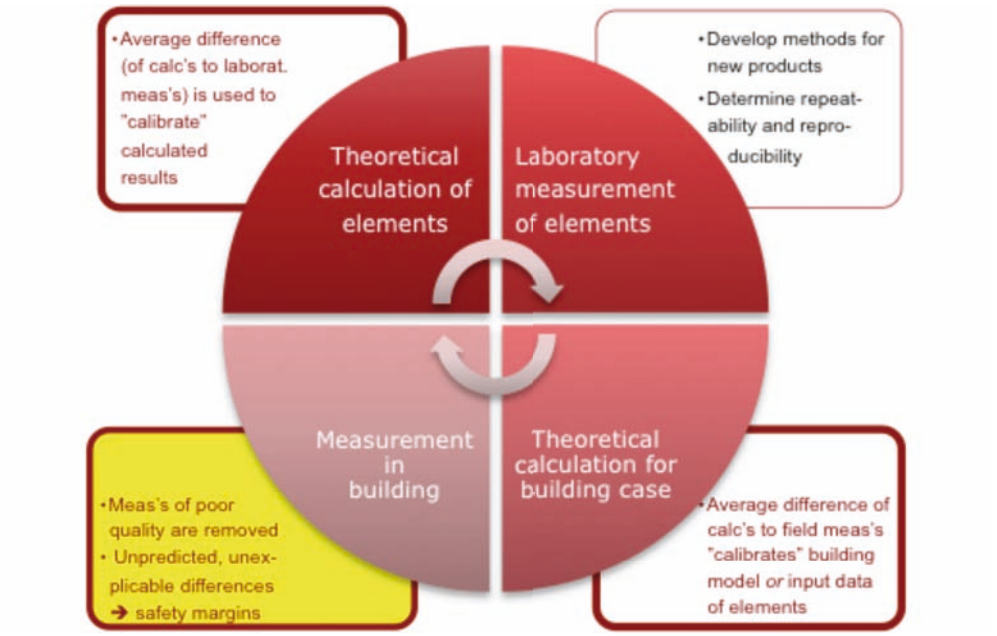


Figure 7. Procedure used to establish input data for building elements where it is impossible to find laboratory data (e.g. in old houses, refurbishment projects etc) and to verify these by comparisons with laboratory and field measurements. C.f. section 3.2.2.

It should be noted, that if a calculation model (software) is improved to incorporate effects that were previously corrected for (manually) after empirical comparisons, the scatter of results may be reduced compared to field measurements. Then the input data of elements may have to be corrected as well. Such revisions should only be undertaken only after careful compari-

[p] A few examples may illustrate this problem: a) new stiffening profiles had been embedded in a PVC window sash without updating the product description, b) the surface weight of a concrete slab was reduced from the agreed value by encapsulating EPS blocks inside the slab (made to increase span width), c) unexpected air gaps between panes of a door (intended to be glued) changed the stiffness and introduced new resonances, as compared to the product description.

sons of results[q]. Some applications of these procedures are discussed in the following sections.

3.2 Walls and slabs - airborne sound insulation

3.2.1 Data for new building elements

Data from laboratory measurements of many types of building products, e.g. light weight plasterboard walls, air inlets, windows, doors, linings, flooring etc, are readily available[8 27].

Pedersen made a broad and systematic analysis of concrete walls and floors in a NORDTEST project in 1997[25], where input data (to parts 1 and 2 of EN 12354) were described in the frequency range of 100-3150 Hz for a variety of constructions used in apartment houses in the Nordic countries[r]. The input data of heavy elements were first calculated according to methods described in the informative annexes of the EN 12354 (parts 1 and 2) and then modified as described in the NT technical report 425[25]. In a special study commissioned by the Swedish Precast Concrete Federation (Betongvaruindustrin), Pedersen extended the analysis to precast hollowcore slab elements (HD/F) and developed a special model for the estimation of their airborne and impact sound insulation in moderately sized rooms. The technical note[26] describes the changes of the calculation models.

Data for the most typical homogeneous concrete walls and slabs, as well as HD/F slabs, were calculated by means of Pedersen's revised models[s] and published in 2001 in the "Nordic database" that supplements the BASTIAN software[27]. These data have since been used by acoustic consultants in the Nordic countries (SE, DK, NO, IS, FI)[t u].

The results of Pedersen's comparisons with field data[26] serve as an example of the outcome of a comparison between field tests and theoretical calculations. The sound insulation of concrete elements was increased in the vicinity of the coincidence frequency (f_c), since the field measurements in ordinary sized rooms in dwellings rarely exhibited any "weak zone" at f_c as would be anticipated by the theory. (The coincidence is a well known phenomenon of plasterboard walls, where the weak part of the sound insulation close to f_c is pronounced by an approximately 10 dB reduction, compared to values one octave band below the f_c). Other data at low frequencies may be more appropriate for very large walls or slabs, e.g. high partition walls between cinemas, auditoria etc. The thick-plate correction according to eq. B4 in annex B1 of the EN 12354-1 was applied for all frequencies (not only those below the plateau frequency).

Warnock has recently made available to the public a calculation software (Sokrates) for the prediction of airborne sound insulations of plasterboard walls on studs[28]. This software is fully empirical, it utilizes measurement data from the laboratory of the Canadian National Re-

---

[q] The first regular 5 years review of EN 12354 parts 1-4 did not lead to any comments from the member states with respect to the calculation models of heavy constructions. CEN is not responsible for the input data, which are typically managed by the users or local database owners. The suggestion to CEN TC 126 was to amend the models for light building systems, particularly in terms of vibration attenuation at junctions and radiation from flanking constructions below the coincidence frequency.

[r] The author and participants from other national laboratories in the Nordic countries contributed data to this project. This database has since been continously amended with the aid of the building industry and acoustic consultants in the Nordic countries.

[s] This calculation model was based on Pedersen's comparisons with some field measurements.

[t] No changes have since been made to these data. Some users of the database have reported good agreement between their predictions (in general) and their own field measurements.

[u] Comments by the users have led to several changes being made to additional layers in the database,. As a consequence of this "live learning process", modified data of e.g. flooring have been entered into the database on completion of new laboratory or field tests. Since 2007, the underlying test reports are audited before data are entered into the database, c.f. the BASTIAN web-site[27]. Some application issues (FAQ) are explained on this website and also discussed on a web-forum for acoustians (ISAC) in order to support a living learning process.

search Institute (NRC) in Ottawa[v]. For the reasons mentioned above, the present author prefers to "calibrate" a software by means of comparing its results to data from several laboratories and various types of product as the conditions at a single laboratory might introduce atypical systematic errors. An example is provided in the following section.

3.2.2 Data for old houses (renovation projects)

In Sweden, the modernization of old apartment houses is an important and growing building activity, e.g. infill development, expansion of attic stories and conversion of other types of building into dwellings. Some years ago, severe annoyance was reported among the residents due to poor sound insulation between new and existing dwellings.

As a consequence thereof, sound insulation now has high priority during the planning process. The standard on sound classification of dwellings[19] explicitly advises that building acoustic documentation should be presented at an early stage of a project, based on calculations or measurements. Measurements in the building are often required, but they can only confirm the actual conditions. Predicting the acoustic performance of a renovated building (where major changes to the construction have been undertaken) calls for theoretical calculations.

Calculations of airborne and impact sound insulation of older Swedish buildings were previously hindered by a lack of reliable data. There was some empirical knowledge of typical acoustic problems within houses from the 1950-, -60 and -70 decades[85], but it was not structured in such a way that it could be easily applied to future projects. With the retirement of several experienced acoustic engineers close at hand (2000-2004), there was an urgent need to document their empirical and theoretical knowledge of old houses. A survey was undertaken among these experts, and some literature data were also gathered.

It was realized that the complex range of constructions typical for old houses had to be described in a schematic and structured way. Otherwise, the amount of variations in construction and sound insulation data would have made it impossible to establish a practical and easy to use database of constructions.

Fortunately, an architectural survey had been undertaken in Sweden some years earlier[29], and the constructions typical of each decade from 1880 to 2000 were described and illustrated therein. The task was then to assign acoustical properties to the constructions listed in the survey. A sound insulation database of some 170 typical constructions suitable for the calculation of sound insulation *in situ* in accordance with the EN 12354[1 2 3] was then established which included data on appropriate renovation measures and some risk factors 'to keep an eye on' [30].

A structured approach to finding consistent data for these constructions was established and was presented at the inter-noise congress in Prague in 2004[31]. The strategy chosen was to combine all methods and data available as illustrated in the Figure 7 (above).

- INSUL calculation software[32] was used to analyze a variety of constructions that had been measured in several laboratories (but were not directly applicable). An *empirical correction* was then established for each category of construction, on the basis of the average and random variation of difference between the calculated and measured sound insulation in the laboratory.
- The input data of each construction in the database (from the architectural survey) was calculated with INSUL and adjusted by the *empirical correction* of the category.
- Sound insulation in some existing buildings was estimated using BASTIAN software[27] (with input data derived in the previous steps) and the results were compared with field measurements.

After the comparisons with field data, some additional corrections were made to certain items of input data. One correction serves as an example with great practical implications in Sweden; the light weight 70 mm aerated concrete wall elements. The retired acousticians and one

[v] This tool was published recently, and the author has not yet made any comparisons with its results. As discussed in section 3.2.2, INSUL software[32] has been applied and according to its developer (Keith Ballagh at Marshall-Day Acoustics) compared extensively with the NRC database.

of the manufacturers who participated in the construction of houses with these elements in the early 1970's finally presented a plausible hypothesis as to why the calculation results differed considerably from the field measurements. It turned out that in Sweden, these elements were mounted in a special manner, i.e. vertically and pre-stressed between the bottom and top slabs. Since there was hardly any plaster on their surfaces they were very reverberant and had an extremely low sound insulation in the mid frequency domain (about their coincidence frequency). When the same material was used for masonry walls with a small gap to the top slab and plastered on both sides, the resonant transmission decreased substantially. To provisionally cope with this effect, two sets of data were entered into the database, one for each type of mounting. This topic should be investigated further, but as the market for such products has decreased the industry has only a minor interest in resolving this issue.

It was also found that some building constructions were difficult to approximate by the relatively simple EN 12354 model. For example, vertical transmission where only lightweight partition walls are placed on very large heavy slabs, e.g. in cellular offices or horizontal transmission between attached row houses. It emerged that the absorption of these slabs (as seen from the sending room) may be provisionally increased to its maximum value 0,5 (according to EN 12354-1, annex C) to fit the field measurement results. However, it would be valuable to investigate this application further.

As illustrated by the above examples, the 3-step procedure combined to some extent the consistency of calculated data with the legitimacy of measured data[w]. As previously mentioned, the empirical corrections were established for each type of construction, e.g. light weight inner walls and external facades, lightweight concrete walls, windows and flooring. An example of an empirical correction is presented in Figure 8 taken from the inter-noise paper (*next page*).

The empirical correction was calculated from the average difference between the calculated and measured values in order to correct for the systematic error. This means that if the calculation overestimates the averaged measured performance, the next calculation case can be reduced by the empirical correction to resemble a plausible average measurement result.

If the calculated value (corrected by the average difference) would be taken as the final result, the probability of underperformance were actually 50%, which would be unpractical for most applications. A safety margin must take account of uncertainties due to workmanship and measurement errors (random variations). Hence in most cases, the empirical correction was taken as the sum of the average difference and one standard deviation.

Calclation results with INSUL corrected by these empirical corrections can be assumed to give an estimated risk of failure of 16% when they include the average difference and one standard deviation, but this is only valid under certain assumptions[14], e.g. that the probability density function of the empirical correction values approximates a Gaussian density function and the data used to derive it are independent and representative of the type of elements[x]. This idealized situation is illustrated by Figures in section 2.4.1.

The distributions of real cases have been plotted In section 4.1.2. These distributions do not exactly follow the normal distribution, but have a similar tendency. This means that the safety margins may still be applicable although a chosen coverage factor (e.g. 1 or 1,28) does not correspond exactly to 16% or 10% risk of failure.

---

[w] A few participants at the inter-noise conference in Prague commented that this was an innovative procedure although no new theory was presented.

[x] These assumptions are probably reasonable but unlikely to be fulfilled completely unless very extensive comparisons are made (>30 measurements for each type of construction would be desirable). The uncertainty increases with smaller samples and coverage factors from the Student t- distribution are more realistic than the Gaussian.

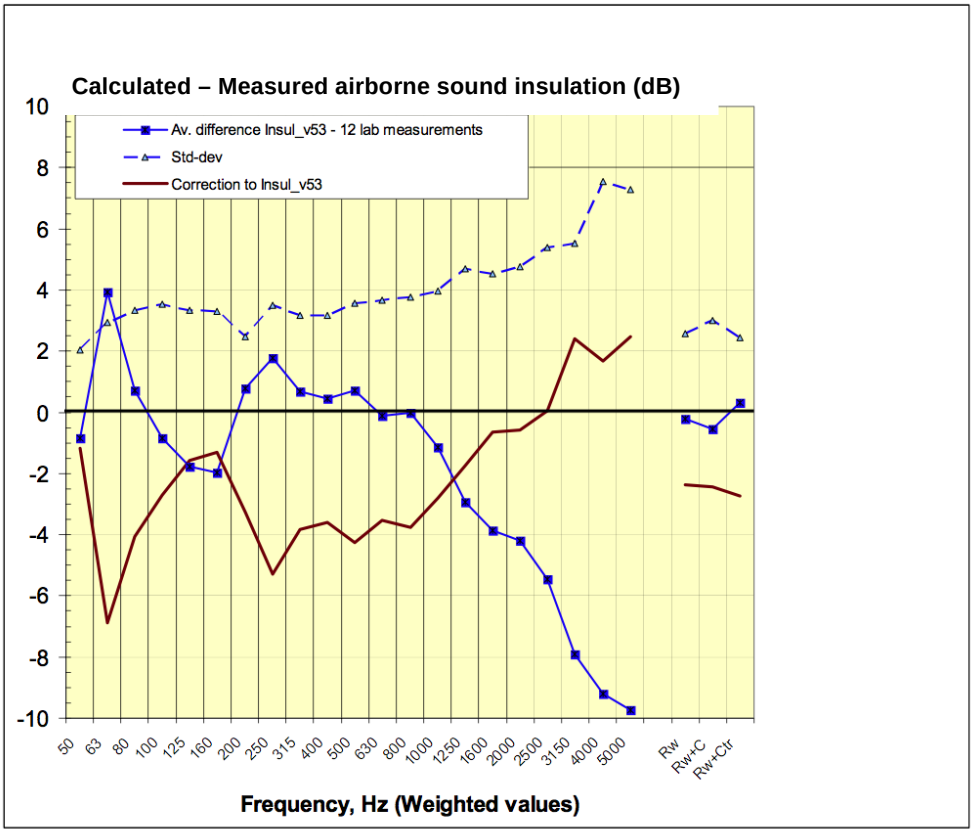


Figure 8. Squared line; the average difference between calculated and measured airborne sound reduction indices in third-octave bands and weighted single numbers. Dashed; the standard deviation. Without marks; the empirical correction that should be added to the calculated results is the average increased by 1,28 times the standard deviation. Based on comparisons of 12 lightweight external walls with various types of insulation and cladding on wooden battens.

Furthermore, database users are recommended to keep a safety margin between sound insulation *in situ* calculated according to EN 12354 (with this product database) and a required value. This margin must be defined by the client or acoustic expert and should take all relevant uncertainty factors into account. When no other information is available, a margin of 3 dB is often used as a rule of thumb (c.f. section 4.1.2). The empirical correction of constructions (elements) should preferably only correct for uncertainties that pertain to the specific construction, i.e. not for general uncertainty. Applying one standard deviation for the input data of lightweight walls was then assumed to provide enough margin, compared to other building elements with less variation in the field. In the case of concrete walls and slabs cast *in situ,*the correction was only made for the systematic difference. Hence, the same general margin could be applied to calculations of field values, including all types of building elements.

As mentioned in the previous section, one disadvantage of the approach presented here is that it has to be repeated if substantial changes are made to the method employed for deriving the data (measurements or theoretical calculations). It should be applied on a local bases since building methods and products tend to vary between countries. On the other hand, the empirical correction may help to determine what needs to be improved.

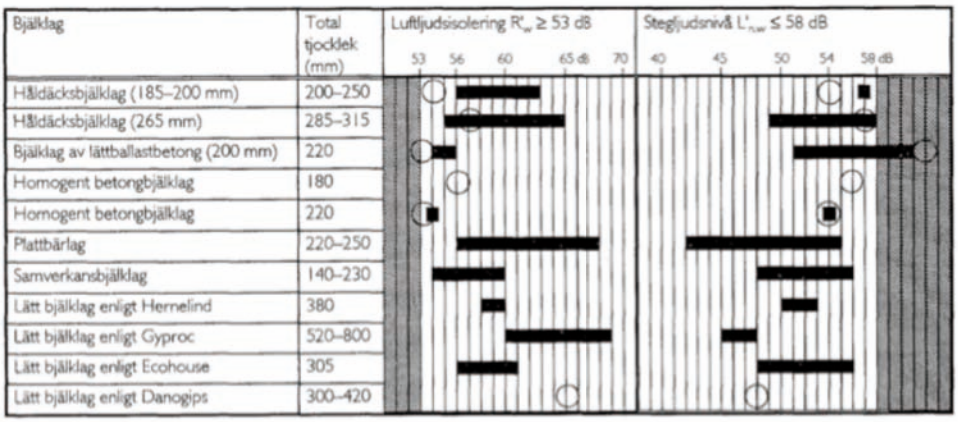
3.3 Walls and slabs - impact sound insulation

3.3.1 Concrete floors

The calculation model in annex B of the EN 12354-2 was applied for homogeneous concrete floors. For precast HD/F concrete slabs, Pedersen's comparisons[25 26] revealed an increasing impact sound pressure level in line with increasing frequency that was higher than expected on the basis of the monolithic slab theory. This was assumed to relate to the joints between the HD/F elements, which do not firmly attach the sides of the elements (with respect to both displacements and rotations). Excitation with the standardized tapping machine (defined in ISO 140-7) concentrates on one or two elements at the time and thus differs from airborne sound excitation that affects all elements within the room.

Some analyses conducted by SBI (Stålbyggnadsinstitutet) with ultrasound equipment and vibration transducers confirmed that there is an increasing attenuation of vibrations across each joint with increasing frequency[33]. This study also comprised an overview of field results for various types of precast HD/F as well as massive concrete slabs. The results are summarized in Figures 9a and 9b (from ref. 33).

The comparison by SBI showed two tendencies that support the application of a calculation model for estimating the performance of HD/F elements in the field: the performances of HD/F were less in the laboratory than in the field; and the variations in the field results were larger than expected (at the time of the study, when the EN 12354 had not yet been developed).



Figures 9a and 9b. The comparison by SBI revealed two tendencies that support the application of a calculation model to estimate the performance and not just evaluate empirical data: a) left, the airborne sound insulation of "Håldäcksbjälklag" (HD/F) in the laboratory (circles) was less than in the field (bars). b) right, the field impact sound levels (bars) varied more than expected at the time of the study and were lower (better) than in the laboratory. From ref. 33.

3.3.2 Wooden floors

An exception to the procedure described in section 3.2 was that the impact sound insulation of light weight timber joist floors was adopted directly from laboratory measurements and their impact sound levels were simply increased by 3 dB. This margin (3 dB) was suggested by consultants on the basis of their empirical experience. The reason for this correction is that their performances tend to be impressive in the laboratory but more moderate in the field. One explanation for this difference may be flanking transmission through the supporting studs and walls, which is not handled by the calculation model in the present version of EN 12354. In addition, transmission losses at junctions between light weight constructions are not yet well described, as mentioned in section 2.2.

Until further knowledge is gained about such constructions, one should keep a large margin to requirements or minimize the use of constructions that are too sensitive to the quality of workmanship. An example from Luleå University of technology (Johansson et al, presented at the Inter-noise 2000[34]) reports the results of impact sound measurements in 170 dwellings with the same type of lightweight floor construction. Figure 10 illustrates that the uncertainty of performance of such constructions should be determined in the field and not only in the laboratory.

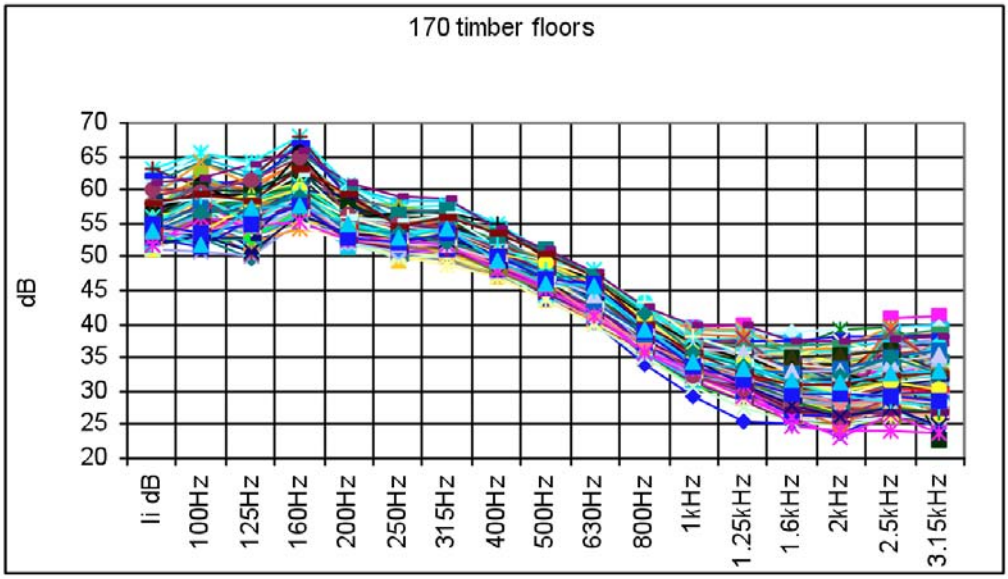


Figure 10. Impact sound level and index for 170 floors. From ref. 34.

3.4 Numerical analyses of vibration reduction at junctions

There are calculation models in annex E of the EN 12354-1 for the estimation of a vibration reduction index of junction between 2-4 homogenous plates. Gerretsen presented Figure 11 (at a Nordic meeting 2008) with an estimation according to a Dutch model and empirical data from Westphal, Gösele and Kihlman. The conclusion was that such formulas might be a reliable basis for K_{ij} when the building elements are homogeneous.[35].

The expressions based on mass ratios have been discussed e.g. in the CIB/WG 51 scientist forum. A study conducted by the author between 1987 and 1988[36] provides some references to analytical approaches to this problem. In many applications however, flanking transmission through more complex junctions plays an important role, e.g. facades or ceilings with plates embedded in profiles of steel or aluminum. A group of measurement standards have been developed for the flanking sound reduction index and the vibration reduction index of junctions (EN ISO 10848 parts 1-4).

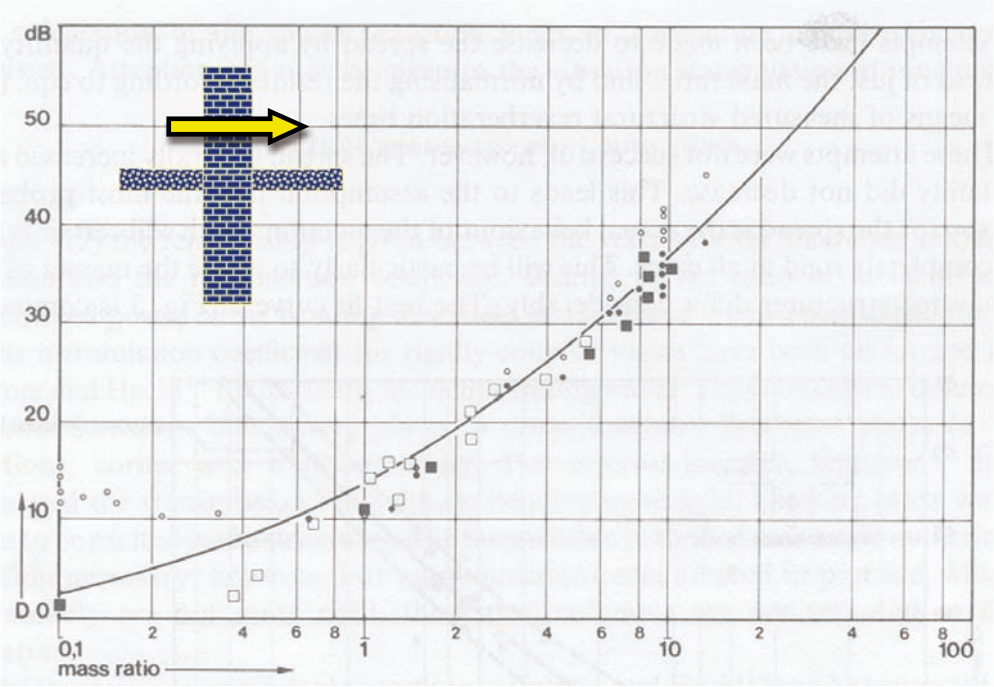
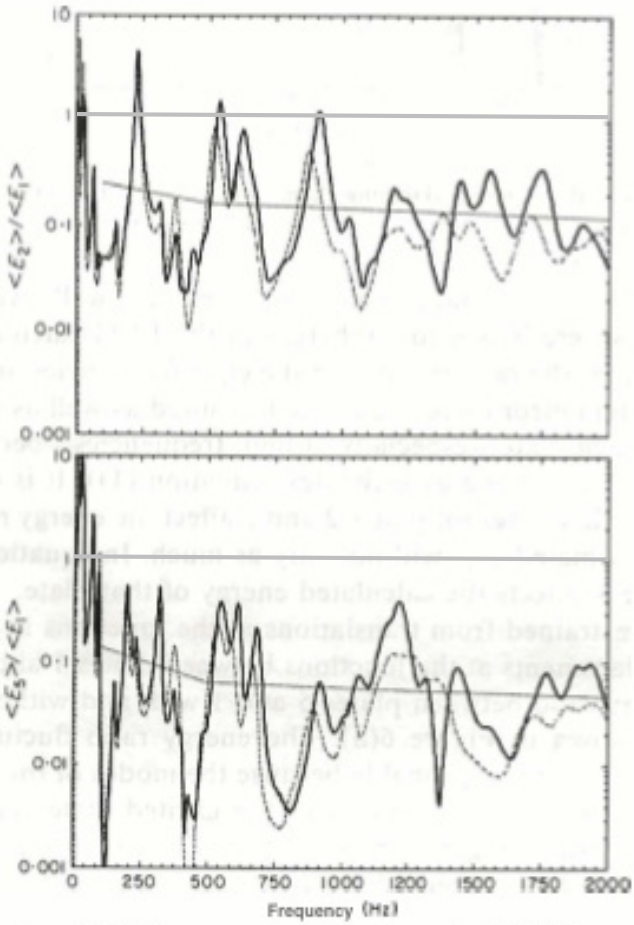


Figure 11. Vibration level difference (D) of two homogenous slabs on each side of a junction in relation to the mass ratio of a massive wall connected firmly at right angles to the slabs. Solid line, calculated according to an empirical Dutch model. Points, empirical data from Westphal, Gösele,calc by Kihlman. The Figure is taken from the proceedings of B-NAM 2008 (Gerretsen).[35] *The values differ slightly from Figure E1 of EN 12354-1 but the tendency is similar.*

The author applied the finite element method (FEM) to estimate the vibration level difference of plates connected to one or two common junctions. The goal was to verify whether FEM could be a general tool for estimating the vibration reduction of junctions of more or less arbitrary shape and hence applicable to complex types of junction.

The calculations in the FEM-study were made for perspex plates, since these have known properties and are easy to attach in order to obtain a completely homogenous junction (it becomes transparent). The first parts of the study explored whether the approach was feasible. The calculation results were compared with measurements made in the same narrow frequency bands and the same discrete accelerometer positions as the mesh in the FEM-model. The results were also compared to values estimated by a SEA-analysis.

An example of agreement between calculations and measurements of the ratio of kinetic energy between the plates is presented in Figures 12a and 12b from reference (36). The “H-model” referred to in the legend to figure 12 can be found in Figure 15 (below).



Figures 12a and 12b. The energy ratios of the H-structure in Figure 15. a) top, ratio of spatial averaged kinetic energies E_2/E_1 between plates 2 and1. b) bottom, energy ratio E_5/E_1 between plates 5 and1. Bold solid lines (___), experimental values in narrow bands. Dashed lines(_ _ _), discrete frequency values predicted by FEM. Thin solid lines show third-octave band values predicted by SEA. Bold solid line depicts equal energy of both plates (their ratio is 1).

The agreement is not perfect in the narrow frequency bands but improves when a frequency band average is calculated. The agreement with the solid thin line, derived by means of an SEA-calculation was reasonable on average. The structural damping of the system was altered a few times within the expected confidence interval, which shifted the calculated values closer or further away from the measured “true” values. The author concluded that although the vibration level difference may be less than expected at some frequencies (meaning that more energy travels from one plate to the other), the agreement could still be satisfactory for engineering purposes provided some averaging is applied.

To improve accuracy, appropriate variation of input data should be made with respect to their expected probability density functions (PDF) and simulation results should then be averaged to reduce the influence of random errors. The author has not performed such analyses, but Mace and Thite presented some work of this nature at the inter-noise conference in Prague 2004[37]. Their paper also lists other articles related to this issue.

Coyette presented some interesting graphs at the LeMans conference in 2005[38] which illustrate certain effects on the frequency response function (FRF) caused by uncertainties in the input data to the FEM-calculations. The main sources of uncertainty can be divided into three categories (Coyette's descriptions are summarized briefly by the author):

- Finite elements and modelling assumptions do not reflect the function of the real dynamic system
- Numerical errors in the model and calculation (interpolations, equation solving..) introduce errors
- - Input data approximate the behavior of the materials, e.g. one must often apply linerized and frequency independent parameters (mass distribution, stiffness, damping)

An impression from Coyette's presentation is that the statistical analysis proposed by the author in 1991 may be more complicated to implement than first anticipated. There are several reasons for this, one being the large number of parameters that have to be randomized. A Monte Carlo technique must be applied since there can be no presumptions about the PDFs of the input and computational parameters, as this would require great computational effort.

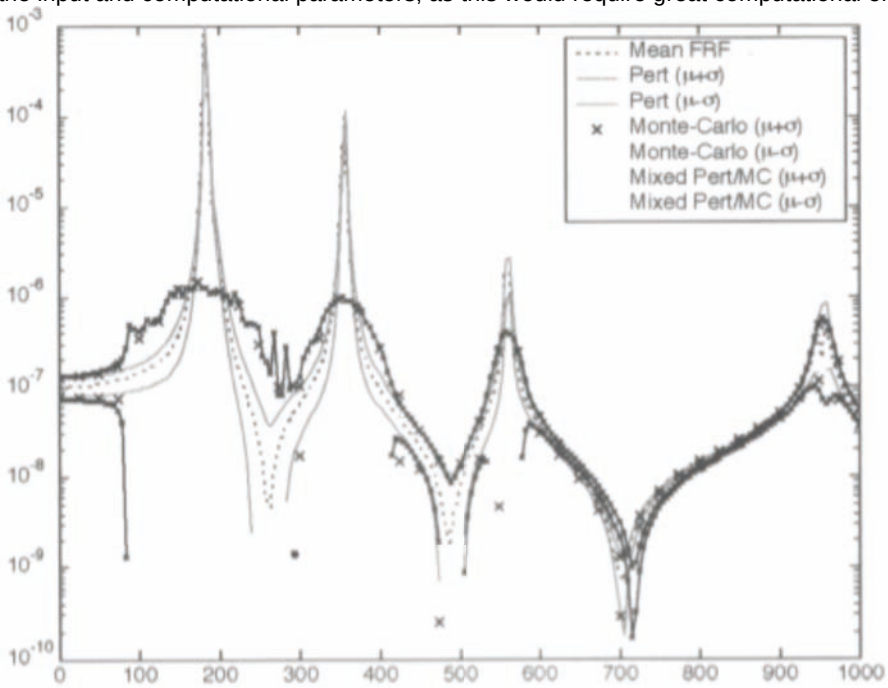
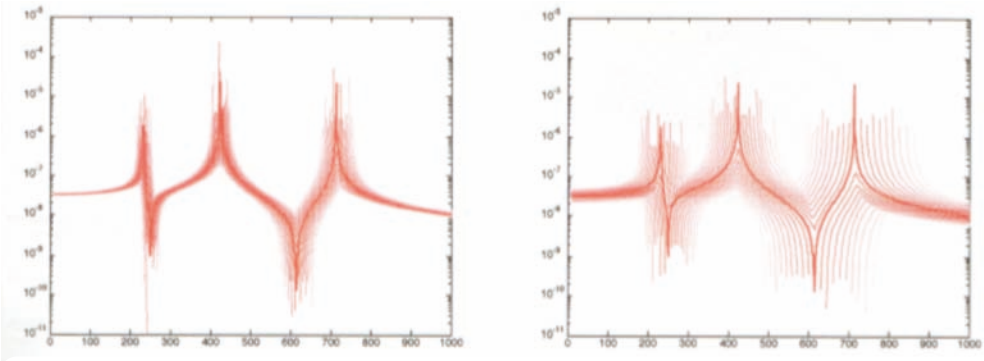


Figure 13. Dispersion of the vertical displacement frequency response function (FRF) for a plate with random flatness default



Figures 14a and 14b. Articulated truss structure; fuzzy frequency response function (FRF) of the displacement field (all parameters having a) left: 3% or b) right 10% of variability

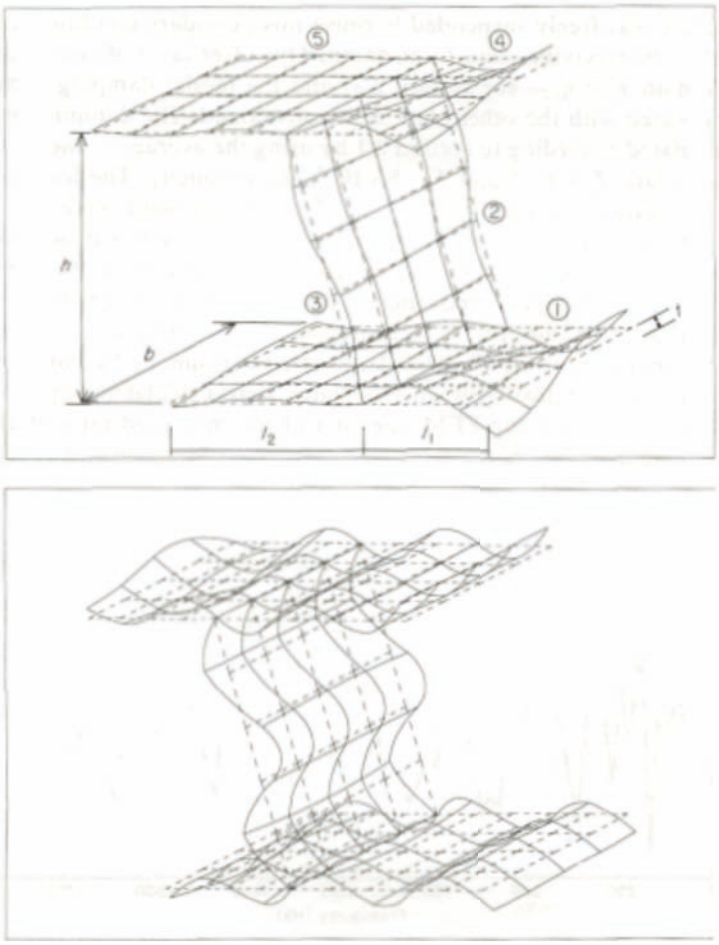
The results presented in Figures 14, taken from Coyette's paper, may increase understanding of some underlying mechanisms behind an empirical observation in the field of building acoustics; that resonant phenomena in narrow bands deduced from analyses of small dynamic systems tend to be "smoothed" in the larger scale of a building. This may explain why SEA-like estimations of vibration velocities tend to fit measured data (in third octave bands) better (on average) than anticipated on the basis of a detailed (deterministic) analysis. This is of course a benefit, from a practical perspective; the opposite would be more troublesome. It is beyond the scope of the present thesis to expand this discussion, but it is certainly tempting to do more work in this area in the future!

The FEM analysis in this author's paper[36] also revealed a phenomenon that is well known in structural acoustics, namely the occurrence of global modes. A plate connected to a plate of the same size and dynamic properties via an intermediate structure of a different size or with different properties may actually vibrate more than expected from a SEA analysis, as illustrated by Figure 15 taken from the same paper.[36] In terms of SEA, this corresponds to a negative energy flow between plates 2 and 3.

It is reasonable to expect global modes of connected plates in buildings where the slabs of different stories are made of the same materials and dimensions[y]. This would reduce the accuracy of predictions carried out in accordance with the EN 12354-5 (compared to field measurements), particularly where there are several wall or slab intersections between the plates. Unfortunately, most field measurements known to the author were made in the vertical direction, where direct transmission through the slab dominates the transmission. This will be discussed later in this section.

Craik and A. Thancanamootoo examined the effect of including in-plane waves in a statistical energy analysis model of a building[39]. They stated that: "*It is shown that the additional waves make little difference close to the source, but large differences can occur far from the source if they are omitted.*" This phenomenon can be illustrated by Figure 15 (below). The effect of in-plane waves need to be investigated further with respect to their impact on structure-borne sound transmission across multiple junctions.

[y] There are undocumented experiences reported about structure-borne sound where the most disturbing sounds were actually detected several rooms away from the source room. This need to be investigated further.



Figures 15a and 15b. Five Perspex plates forming an H-structure, suspended in soft springs, excited vertically at the corner of the plate 1. Dashed lines; the element mesh. Solid lines, illustrating two mode shapes. a) top figure, frequency 584 Hz. b) bottom figure, frequency 900 Hz.

The main purpose of the author's study was to determine whether FEM could be used to analyze complex junctions between plates, which cannot be analyzed by other models, e.g. modal expressions or statistical energy analyses (SEA). It was concluded that FEM can indeed be used for such analyses, but great care has to be taken to ensure the validity of the numerical analysis, i.e. that it yields reliable results[z].

A verification procedure was suggested, where numerical results are compared to analytical results, using structures that can be calculated exactly. An example is presented in Figure 16 from the paper[36], where the FEM results are compared to a frame analysis that is assumed to be exact (i.e. exact when all conditions apply in reality). It appears that in this case the FE-analysis was in good agreement.

[z] When this study was planned, several researchers were sceptical about this approach and this author could find no previous study to support it. However, computer resources were rapidly developing and their costs reducing, which may be one reason for why this approach had not yey been applied.

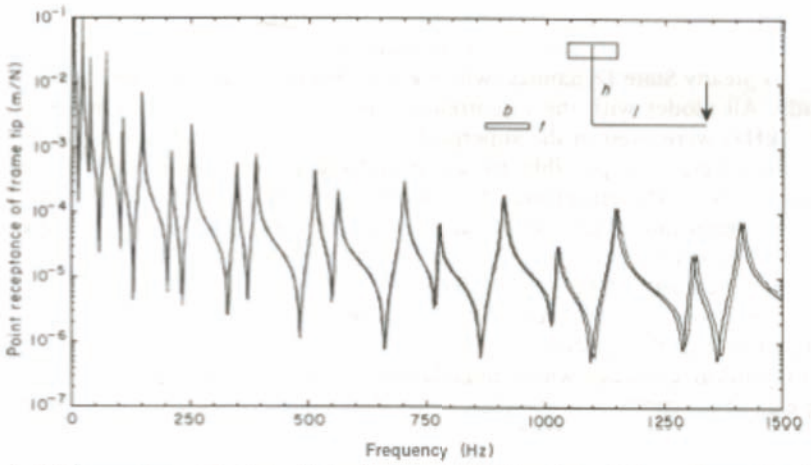


Figure 16. Point receptance (displacement/force) of the free end of a steel frame, with the other end clamped. Solid lines; predicted by means of an exact frame analysis. Dashed lines; predicted with FEM. Dimensions and material properties of the structure, c.f. ref 36.

It was also proposed that consecutive FEM analyses might be applied in order to estimate coupling loss factors for SEA analyses of complex systems in which the specific type of junction appears. Guyader later suggested this as well[40]. However, as mentioned above, this part of the work remains to be done and is not discussed further in this thesis.

3.5 Façade elements - airborne sound insulation

For many years the Swedish requirement on the protection of dwellings with respect to external sounds has been expressed as the highest sound pressure levels that may occur in the dwelling, given as the L_{pAeq} (the A-weighted 24 hour equivalent sound pressure level) as well as the L_{pAFmax} (the A-weighted maximum sound pressure level with F time weighting). This requirement may appear clear with respect to the protection of the inhabitants, but practical experiences reveal that it is very complicated to implement and verify in building projects.

Many questions have been raised during the planning phase: which traffic conditions should be assumed for the estimation of the outdoor sound pressure levels? Who is responsible for the composite sound insulation of the facade (i.e. the outer walls, windows, air inlets etc)? Is the maximum sound pressure level the highest value that can occur at any time, or an average of events?

The sound classification standards[19 20] and the Boverket handbook [85] provide guidelines that clarify some of these questions. In 2003, this author proposed a change that was adopted in 2004; the requirement is expressed directly as a sound insulation requirement, the value being determined from the outdoor sound pressure level provided by the client or the authorities. The definitions of outdoor sound pressure levels include application conditions, i.e. they state that the levels refer to yearly traffic averages. The designer was assigned responsibility for the sound insulation of the facade, which implied selecting appropriate products with respect to the margins for the types of products used in the actual building. This procedure is described in a Euronoise paper from 2006[41].

Sound insulation of windows and the main sources of uncertainty in the determination of their insulation in the laboratory as well as in the field, are discussed extensively in a 1998 report (*in Swedish*)[42]. Experiences of the performance of windows in the field were reported by Jonasson in 1985, based on which a general safety margin of 3 dB was recommended[43]. This

value may be appropriate for many types of window, but there are both better and worse experiences with modern windows that call for individual assessment of the safety margin needed for each product including and its mounting method.

Hveem and Homb presented "Håndbok 47 – Isolering mot utendørs støy"[44], a detailed and widely used façade insulation handbook.

Saarinen examined sound insulation in the field compared to estimations made with the EN 12354-3. This Finnish study revealed a standard deviation of 3.8 dB in the difference between the calculated and measured values of twelve facades[45]. The 3,8 dB systematic deviation should be examined further by looking carefully into the underlaying assumptions.

The location of the outdoor microphone is described in ISO 140-5. This issue has been discussions for many years as it seems that consultants do not feel confident about the ISO-method for all circumstances in the field. For instance, Bradley and Chu examined some problems related to the measurement of incident aircraft noise[46] and recommended free field positions for the microphone rather than façade-mounted microphones. Other studies on this issue were found but explored further[aa].

3.6 Structure borne sound from service equipment

The section 4.4 of the EN 12354-5 describes models for the prediction of structure-borne sound from service equipment[bb]. Gerretsen provided a short background to the standardized calculation model at Inter-noise 2000 in Nice, France[47] and Euronoise/Acoustics in Paris in 2008[48]. To apply the model, input data for all equipment used in buildings (sources) should be determined and made available to the designers. To the knowledge of the author, no comparisons with field measurements exist. In this section, only methods to derive input data for sources are discussed.

3.6.1 Determination of equivalent forces of weak sources on heavy supporting structures

A new measurement standard was issued by CEN in 2009; the EN 15657-1 for laboratory measurements of structure-borne sound power of equipment with high mobility placed on building structures with low mobility. This method is based on a so-called reception plate, on which the equipment being tested is mounted. The average vibration velocity levels of the plates are determined during operation of the source. The injected power is indirectly estimated from the power losses of the reception plates, which are assumed equal under steady state conditions. The basic principle of this method is similar to the well-known ISO 3741 method for airborne sound power measurement in a reverberation chamber.

Schievenels, De Geeteren and Ingelaere described an application of the EN 15657-1 at the inter-noise 2009 in Ottawa, Canada[49]. They described some promising agreements but also pointed out several complications that need to be investigated further: " *The promising results with the ISO tapping machine show that the RPM assumptions are valid with this broadband source and that the model parameters in EN 12354-5 are well estimated by the annexes in EN 12354-1. Only for lower frequency bands, there are larger deviations between predictions and measurements. These might be due to limited eigenmode density on the reception plate and/or less accurate estimations of model parameters by EN 12354-1. The results for the washing machine depend on the mounting… If the concrete base*[cc] *is shortcut by jacks as supports, the agreement between prediction and measurement is comparable with the ISO tapping machine case, suggesting that the RPM can also be used for low-frequent tonal force sources*."

[aa] e.g. 1) Testing the acoustical corrections for reflections on a façade. Memol G. et al. Applied Acoustics Vol 69, Issue 6, June 2008. 2) A method for field measurement of the transmission loss of building facades. P.T. Lewis Journal of Sound and Vibration, Vol 33, Issue 2 March 1974. 3) Sound fields near building facades – comparison of finite and semi-infinite reflectors on a rigid ground plane. C. Hopkins, Y. Lam. Applied Acoustics, Vol 70, 2009.

[bb] The section 4.2 of part -5 describes a calculation model for airborne sound transmission through ducts from service equipment. This issue has not yet been addressed by the author, but some manufacturers have been informed about the new standard (2009). The part 4.4 also provides examples of structure-borne typical sources in buildings.

[cc] The base was actually a MDF-board on the jacks, not the concrete base, its mobility being considerably higher.

A field method has been developed by the author in cooperation with Larsson (SP Borås)[50] on the basis of principles suggested by Gerretsen (TNO). It has now been adopted as the NORDTEST method NT ACOU 117[51]. The method is based on the principle of substitution. The vibration levels of a more or less arbitrary heavyweight reception plate are first measured when a source with high internal mobility is in operation. The vibration levels are then measured at the same positions on the reception plate when a substitution source is in operation. The substitution source employed in NT ACOU 117 is a standardized tapping machine in accordance with the ISO 140-7 as is also used to determine impact sound of floors. A round robin test of this method has been performed, where a heavy laundry machine on three different bases was used as a source, as illustrated by figure 17 from a paper submitted to the Noise Control Engineering Journal[52].

There were critical arguments against the reproducibility of the substitution method in the course of preparing the pilot study. The source strength determined either by comparison with a tapping machine (standardized in EN ISO 140) or by the method in EN 15657-1 can be strongly affected by different modal vibrations of the supporting floor which would alter the source strength in a building, as compared to the strength determined in the laboratory. The relation of the performance in the laboratory compared to *in situ* must be well known in order to make the test results from the laboratory to be applicable in practice. It was therefore necessary to perform a round robin test, including dedicated impact sound laboratories as well as realistic buildings with a variety of heavyweight floor constructions.

Figure 17: Electrolux Laundry Systems type Wascator 465H washing machine, on a) the framed base with a MDF plate on 4 hand-operated jacks, b) the concrete filled steel plate base (200 kg) resting on massive steel cylinders, c) the same concrete base resting on Sylomer® soft polymer cylinders (f_0 12 Hz), d) the drum and the eccentric load (a 1,5 kg steel plate screwed to the side of the drum)

Figure 18 (*next page*), which is also taken from the NCEJ paper illustrates the result of the inter-laboratory comparison.

In the round robin study, the differences between the vibrations from the washing machine and the tapping machine were calculated from the spatially and logarithm averaged vibration level of each source, essentially following the ISO 140-8 standard for determination of the reduction of the impact sound of flooring.

Subsequently, another way of calculating the difference of vibration levels was examined, and finally adopted in the NT 117 method (instead of the ISO 140-8 method). In the NT 117-method, the difference in level at each accelerometer position was averaged arithmetically over all source and accelerometer positions. That is, each difference is regarded as an independent estimate of the vibration level difference (and hence force level difference) of the source compared to the tapping machine.

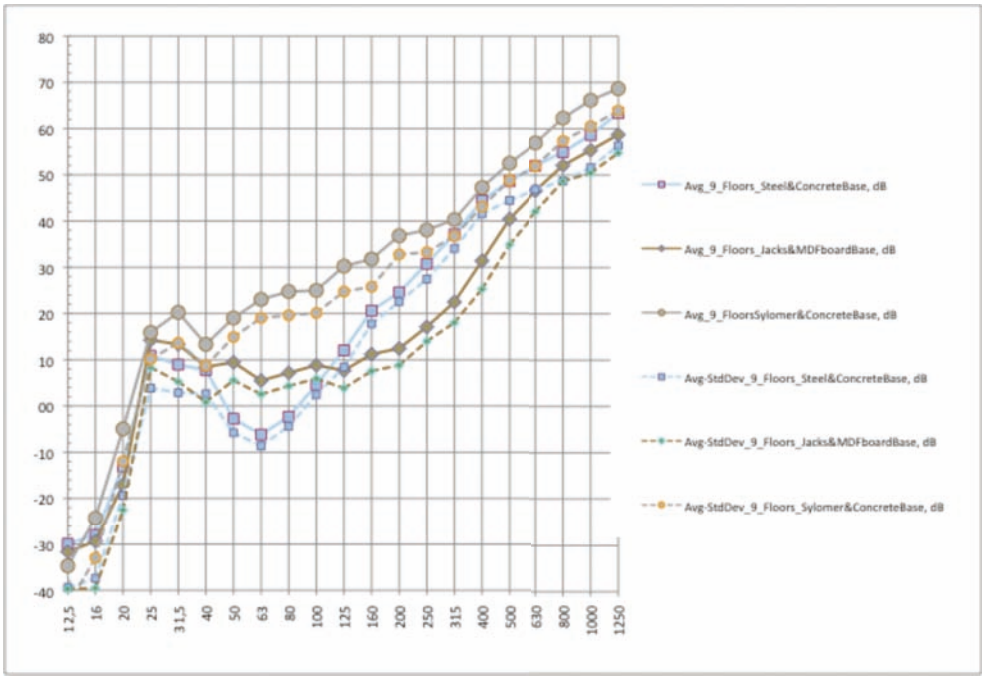
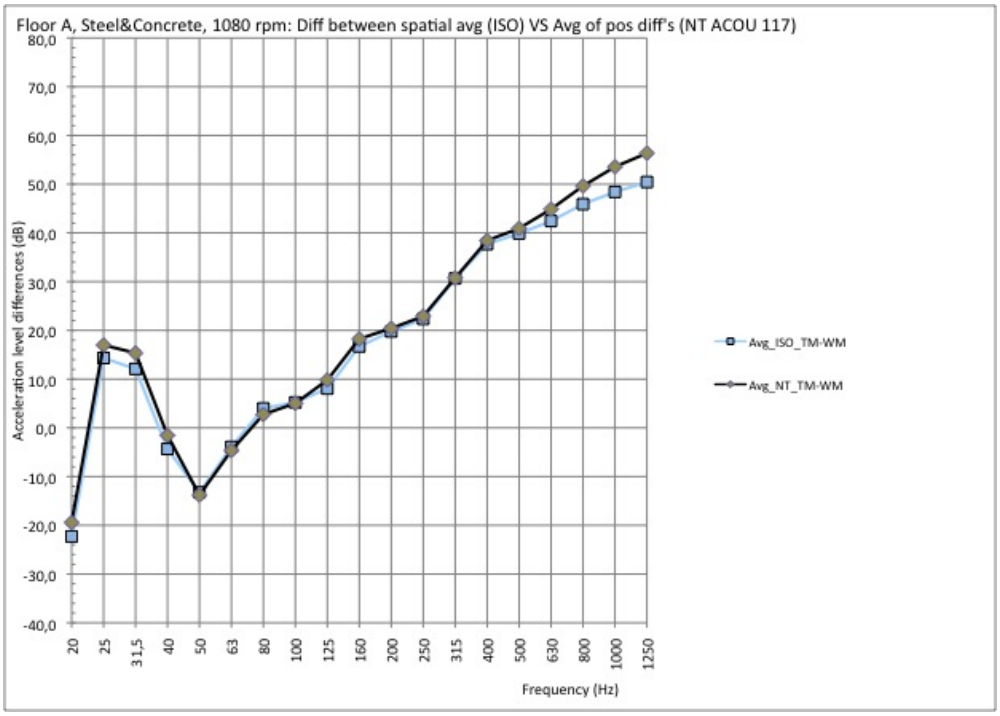


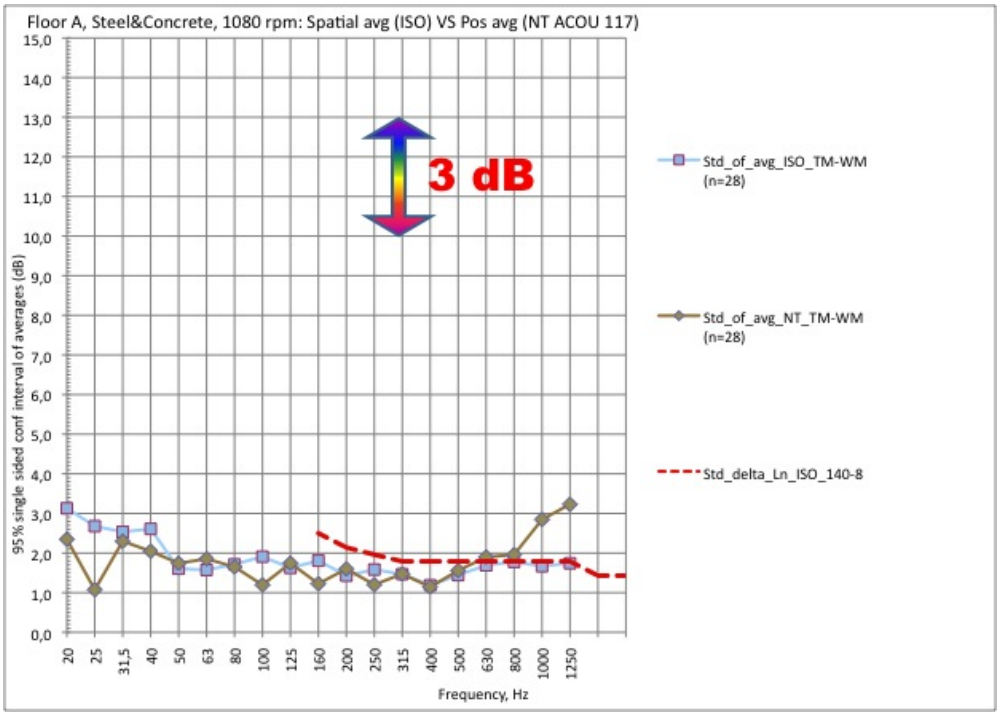
Figure 18. Solid lines indicate differences between the spatially logarithm-averaged vibration levels of the standardized tapping machine and the washing machine on three types of base, placed on 9 concrete floors. Averages of 4 speeds 720-1080 rpm (12-18 Hz). Dashed lines show the same differences but reduced by one standard deviation of the differences determined by the participating laboratories. In an individual case, the scatter of results could vary much more among different positions of the source, rotational speeds etc, see below.

Therefore, the arithmetic average difference of levels determined in each position is used. Their standard deviation is calculated. According to NT 117 the final result is the average reduced by one standard deviation (of the average) in order to compensate somewhat for the uncertainty of the method. In cases where only one source position is used, two standard deviations should be subtracted from the average. The Figures 19a and 19b illustrates the averages and the standard deviations of the average using the two methods of averaging, calculated for one specific mode of operation, using one machine base and one floor.

The standard deviations in Figures 19 refer to half the confidence interval of the average, for the 28 results used, using 1,7 as a coverage factor. The standard deviation between individual positions is about 2 times larger than shown by the confidence interval of Fig. 19b.

The NT 117 is a simple and robust measurement method suitable for use as a survey method. The lack of a practical method has been a major drawback for the building industry, particularly manufacturers of building service equipment such as HVAC systems, elevators, laundry machines, sanitary equipment and kitchen furniture. The results from the round robin study were satisfactory and a NORDTEST method was adopted in 2009[51]. However, there may still be a need for laboratory methods with higher precision that justify the use of more advanced measurement resources to be applied. Greater efforts should be made to develop and test methods that are both practical and accurate. They should preferably handle the need to characterize a machine at different rotational speeds (e.g. an interpolation scheme) as well as presentations of some weighted single numbers. Some kind of classification scheme could be developed to guide consumers to choose machines that are not likely to disturb neighbours.





Figures 19a and 19b. a) top; spatially averaged vibration levels determined in two ways. b) bottom, the single sided 90% confidence interval of the averages (n=28, coverage factor 1,7)

3.6.2 Point mobility measurements on thick concrete structures

In 1987, the author conducted a short study in cooperation with Kihlman and Peterson on the measurement uncertainty of point mobilities of concrete slabs[53]. This study may be of interest with respect to the use of the EN 15657-1, where the point mobility of the reception plate is determined.

Previous works by Peterson raised the question as to whether ordinary force and vibration velocity transducers could be applied directly to the surface of a concrete slab, or if special intermediate devices should be used. This question was raised because it had been observed that the local deformation of the surface of the concrete slab introduced a “spring-like” impedance between the transducers and the plate, which acts as a vibration isolator between the transducer and the slab. This is illustrated by Figure 20 taken from the report.[53]

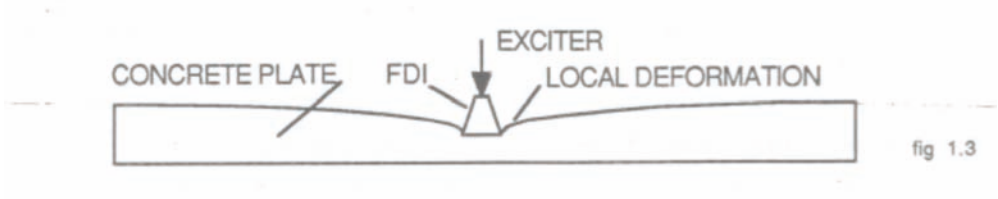


Figure 20. Displacement of the surface of a concrete floor, when excited by a local force on a small surface. From ref. 53.

In a point mobility measurement, the local deformation of the surface turns the phase of the complex mobility of a heavily damped plate from almost zero (with a rigid surface) to close to 90 degrees. An error of one degree in the detectors of the signal analyzer and transducers corresponds to a fraction of a decibel when the phase is close to zero but increases to almost 1 dB for phase angles of more than 80 degrees. Furthermore, if this increased motion would create additional losses (friction, viscous motions of the particles of the concrete), the real part of the mobility would not be reliable for estimating the vibration power injected into and propagating to all parts of the slab. Fortunately, it was concluded that if the vibration transducer can be placed on the opposite side of the force transducer, or an indenter applied to increase the surface of the force transducer (and hence reduce the local compliance of the surface), the measurement accuracy is not seriously affected by local reactions at the point of excitation. The principle of the indenter is illustrated by Figure 21 from the report.

Another method is to place two accelerometers on each side of and at a short distance away from the force transducer, from which the average accelerations are used for the mobility ratio. The author has no knowledge of the accuracy of this (latter) method.

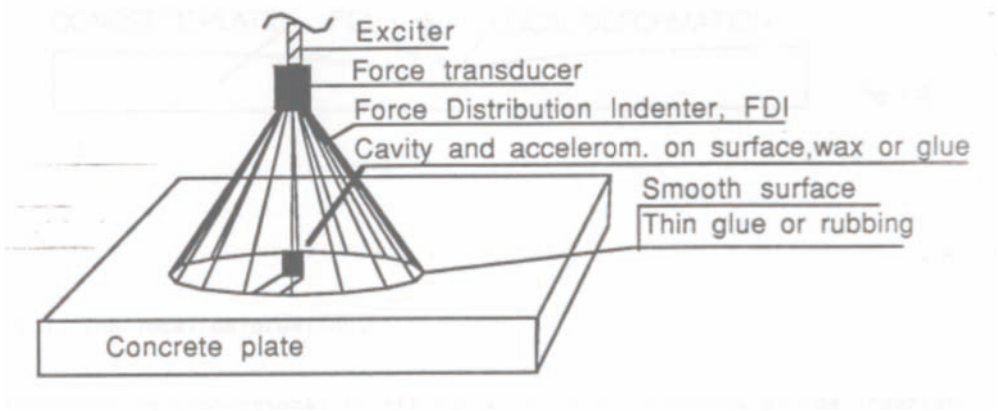


Figure 21. A force distribution indenter, as suggested by Peterson. From ref. 53.

3.7 Sound absorbers for reverberation control

The absorption of sound for specific products (absorbers, acoustic ceilings etc) as well as for generic objects (cupboards, shelves, chairs, curtains) etc. may be determined in the laboratory according to ISO 354 or the similar ASTM method (C 423). At the DAGA conference in 2009, Vercammen presented the results of a round robin in which 13 laboratories participated, and concluded[54]:

" *It is known that the inter laboratory reproducibility of these measurements is not very well. At this moment the differences of results between laboratories are much larger than can be accepted, e.g. from a jurisdictional viewpoint in case of building contracts and liability.*"

An example of the scatter of results are taken from Vercammen's paper:

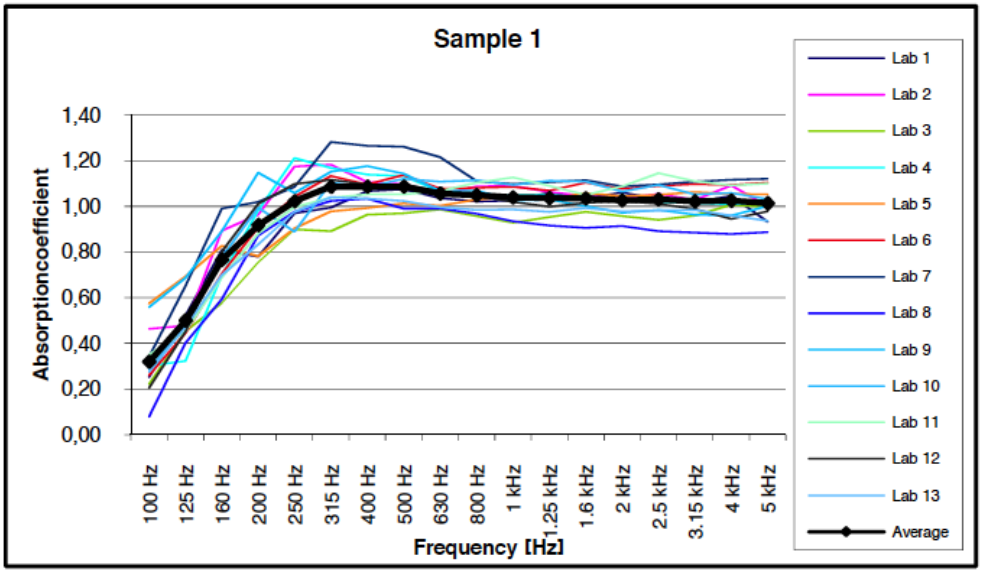


Figure 22. Measurement results of the sound absorption in 13 laboratories. The solid black line gives the average result. From ref. 54.

Other round robin studies will be performed in order to evaluate new mounting conditions[dd].

Another source of uncertainty is the translation of sound absorption of materials and products into an estimate of the reverberation time of a room, which must fulfill certain requirements. In SS 25268, the designer is assumed to calculate the amount of absorption that must be present in a room in order to meet the prescribed reverberation time.

There are three requirements that must be fulfilled in each type of premise, e.g. the classrooms within the same school unit:

- the average reverberation time in octave bands 250-4000 Hz ≤ T_{req}
- the reverberation time in each of the octave bands 250-4000 Hz ≤ T_{req}+0,1s
- the reverberation time in the octave band 125 Hz ≤ T_{req}+0,2s

However, the building industry wants to apply simple design rules and not make calculations pertaining to each individual room. Some common design schemes were presented by this author, with the purpose of facilitating the choice of sound absorbers[55].

[dd] CEN/TC 126 formed a working group (WG 11) in 2008 to develop test codes for suspended, acoustic ceilings. The goal is to determine differences in laboratory measurement results and to suggest better mounting conditions in order to improve the reproducibility of the tests. Several European laboratories are invited to participate in a round robin test of sound absorption measurements aimed at evaluating changes in mounting conditions.

The classification system for absorbers in to the ISO 11654 standard is frequently used in Sweden to prescribe an amount of sound absorption in common spaces. Typically, minimum coverage of the ceiling is prescribed, where any sound absorber of the stated sound absorption class (A-D) is deemed acceptable. The coverage is often given as a percentage of the ceiling area because of its ease. However, there are evident risks that the resulting reverberation may differ considerably from the requirements when this apparently simple procedure is applied, particularly at 125 Hz. Graphs and tables from this paper illustrate this problem.

Tables 1 and 2 (below) were calculated to allow first-hand assessment of the amount of sound absorption that is needed in a room for speech communication, based on a *coverage factor* defined as the ratio of the area of sound absorbers to the area of the ceiling.

The third row in Tables 1a and 1b shows an approximate fraction (in %) of the available commercial sound absorbers in the database that may fulfill the requirement when covering the ceiling as listed in the left hand column. 10% of the database within a sound absorption class typically means that 1-3 products from at least 2 manufacturers fulfill the requirements. 90% means that most products of this class would fulfill the requirements if they cover the larger area listed in the right hand column. If a restricted range of products can be accepted, it is enough to prescribe the 10%-column. If a wider range is preferred, the 90%-column is more appropriate.

The typical absorption value stated in Table 1 is predominantly from the 250 Hz octave band when the product belongs to class A or B. Other octave bands may determine the class and coverage needed for the C-classified products.

Since the ISO 11654 rules do not take account of the 125 Hz octave band, it was necessary to investigate the sound absorption in this band and calculate the required coverage. The results are presented in Table 2. Some plasterboard products with a large empty space to the slab floor (plenum) might have good sound absorption at low frequencies but need additional absorption at high frequencies to meet all requirements. Thus the coverage from table 2 may be greater or smaller than indicated by table 1. Tables 1 and 2 may be too complex for practical applications, thus an attempt was made to formulate simpler tables (see the paper[55]).

The large variation in acceptable coverage of sound absorbers with the same ISO-classification leads to the conclusions that this system would be more useful if it also considered sound absorption at low frequencies (125 Hz) and narrowed the tolerances within each class.

An alternative procedure in line with the EN 12354-6 is suggested in paper[55], based on calculations of sound absorption and reverberation times in the 125-4000 Hz octave bands and taking the relevant conditions of the room into account. This simple calculation scheme provides a table of coverage factors for each of the specific sound absorbing products listed in the database, which is also adapted for all requirements stated i SS 25268. The author concludes, that the classification scheme of ISO 11654 is obsolete and should be removed from the standard.

Table 1. Coverage of classified sound absorber vs. reverberation time of a furnished space. Intended for rooms without requirements at 125 Hz. Room absorption from the handbook[85].

For rooms with T+0,2 sec requirement at 125 Hz, the highest coverage of table 2a and 2b apply.		*Coverage of ceiling with sound absorbers (% of ceiling area), with products of class A-C (ISO 11654)*					
		A		***B***		***C***	
Available products that fulfill T req (%):		*10 perc*	*90perc*	*10 perc*	*90perc*	*10 perc*	*90perc*
Reverberation time T (s)	*Typical absorption Room height (m)*	*0,85*	*0,6*	*0,70*	*0,5*	*0,65*	*0,4*
0,4	2,7	72%	102%	88%	123%	94%	154%
	3,1	87%	124%	106%	148%	114%	186%
	3,5	102%	145%	124%	174%	134%	218%
0,5	2,7	55%	78%	67%	94%	72%	118%
	3,1	68%	96%	82%	115%	89%	144%
	3,5	80%	114%	98%	137%	105%	171%
0,6	2,7	43%	61%	52%	73%	56%	92%
	3,1	54%	76%	66%	92%	71%	115%
	3,5	65%	92%	79%	110%	85%	138%
0,8	2,7	27%	38%	33%	46%	35%	58%
	3,1	35%	50%	43%	60%	46%	75%
	3,5	44%	62%	53%	74%	57%	93%
1,0	2,7	17%	24%	20%	29%	22%	36%
	3,1	24%	33%	29%	40%	31%	50%
	3,5	30%	43%	37%	52%	40%	65%
1,2	2,7	10%	14%	12%	16%	13%	21%
	3,1	15%	22%	19%	26%	20%	33%
	3,5	21%	30%	26%	36%	28%	45%
	4	29%	40%	35%	48%	37%	61%
1,5	2,7	2%	3%	3%	4%	3%	5%
	3,1	7%	10%	9%	12%	9%	15%
	3,5	12%	17%	14%	20%	15%	25%
	4	18%	25%	21%	30%	23%	38%

Table 2. Additional 125 Hz octave band requirement for furnished rooms.

Sound absorption @125 Hz		<0,15	0,2	0,3	0,4	0,5	0,6	0,7	0,8
Class A-C from ISO 11654 % of products fulfilling T+0,2s		A, B, C (90%)				A, B (10%)	C (10%)		
Reverberation time T (s)	*Room height (m)*								
0,4	2,7	347	260	173	130	104	87	74	65
	3,1	418	313	209	157	125	104	90	78
	3,5	489	367	244	183	147	122	105	92
0,5	2,7	278	209	139	104	83	70	60	52
	3,1	339	254	170	127	102	85	73	64
	3,5	400	300	200	150	120	100	86	75
0,6	2,7	227	170	113	85	68	57	49	43
	3,1	280	210	140	105	84	70	60	53
	3,5	333	250	167	125	100	83	71	63
0,8	2,7	155	116	77	58	46	39	33	29
	3,1	197	148	99	74	59	49	42	37
	3,5	240	180	120	90	72	60	51	45
1,0	2,7	107	80	53	40	32	27	23	20
	3,1	142	107	71	53	43	36	30	27
	3,5	178	133	89	67	53	44	38	33
1,2	2,7	72	54	36	27	22	18	16	14
	3,1	103	77	51	39	31	26	22	19
	3,5	133	100	67	50	40	33	29	25
	4	171	129	86	64	51	43	37	32
1,5	2,7	36	27	18	14	11	9	8	7
	3,1	61	46	31	23	18	15	13	11
	3,5	86	65	43	32	26	22	18	16
	4	118	88	59	44	35	29	25	22

4 Field measurements and some comparisons to calculations

4.1 Airborne and impact sound insulation between rooms

4.1.1 Uncertainty of field measurements

A short study performed by the author contributed some information about the expected uncertainty of field measurements and field calculations referring to the same building site (i.e. variations in the properties of the test object were omitted) [56 57].

An inter-laboratory comparison was made *in situ* with the participation of 8 laboratories. The operators measured airborne and impact sound insulation of 7 partitions according to the ISO 140 standards and some additional guidelines. Variations in the airborne sound reduction index and its components were analyzed. In the draft ISO 140-2[14], this test is referred to as a type B-test, where the test objects are the same but the operators and equipment are changed. Table 3 from the paper summarizes the resulting standard deviation and single sided confidence intervals between operators.

Table 3. Variation in the measured airborne sound reduction index and spectrum adaptation terms, measured by 5-8 operators in 7 spaces.

Estimated uncertainties, in decibels, dB:	Standard deviation, 7 (all) cases	90% confidence (1,6*Standard-deviation), 7 (all) cases	Standard deviation 5 regular spaces	90% confidence (1,6*Standard deviation), 5 regular spaces
R'_W	1,0	1,7	0,7	1,1
R'_W+C	1,2	1,9	0,8	1,3
R'_W+C_{tr}	1,3	2,2	0,9	1,5
$R'_W+C_{50-3150}$	1,3	2,1	0,7	1,1
$R'_W+C_{tr,50-3150}$	1,7	2,7	0,8	1,3

The comparison of the results revealed that the main part of the uncertainty in the measured sound reduction index is pertinent to the sound pressure level difference between the transmission and receiving rooms L_s-L_m, which depends on the amount of time and spatial averaging. In the guidelines of the informative annex H of the Swedish standard SS 25267 (written by the author) as well as in the ISO 140, it is stressed that microphone positions must be distributed over the entire measurement space to minimize the spatial sampling errors.

Audits of measurement operators indicate that this is a risk factor in measurement routines when operators do not allow sufficient time to use the number of source and microphone positions needed to reduce the uncertainty of the average. A common explanation for this is the lack of time at the building site, in particular when the construction work has to be stopped during the course of measuring the sound insulation.

The two cases omitted in the right hand columns of Table 3 were measurements in two spaces where it was particularly difficult to measure the sending room sound pressure level in accordance with the standard. One was a very narrow room, the other an open space (an atrium) in front of the receiving room. The values in Table 3 were contributed to the ISO working group dealing with the revision of ISO 140-2[14] (situation B). Table 4 provides estimates of the uncertainty typical of three different types of round robin tests.

Table 4. Standard uncertainties for single-number values according to ISO/WD 140-2[14], in dB.

	Situation A dB	Situation B dB	Situation C dB
R_W	1.2	0.8	0.4
R_W+C	1.3	0.9	0.4
R_W+C_{tr}	1.4	1.0	0.5

One of the variables that affects the sound insulation was discussed in this paper; the sound absorption term which is derived from the area *S* of the common partition, the volume *V* of the receiving room and its reverberation time *T*. The sample standard deviation of the factor 10*log*ST/0,16V* according to ISO 140-4 was determined to 0,6–0,8 dB from the measurements, including the variation in reverberation time *T*.

A brief survey was made among the operators on the choice of *S* and *V* for 5 additional schematic cases with a constant value of *T*. The cases comprised dwellings with open plan constructions, or regular spaces with several wardrobes or a toilet room covering parts of the partition and receiving room. The sample standard deviation was 0,7 dB when one outlier was removed from the data set, and 1,2 dB including this outlier. The results indicated, that it might be worthwhile to attempt to improve the measurement standard instructions to make the choice of *S* and *V* less ambiguous.

Wittstock compiled a variety of uncertainty studies in a PTB-paper (in German[58]), pertaining to the ISO/WD 140-2 type situations A, B and C[14]. He pointed out variation in the production quality of certain elements, e.g. windows, which could depend on seals etc. Aging of elastic materials could also endanger the performance of e.g. windows (air leakage through sills). This scatter of results should be examined by the manufacturer and considered in the properties declared for this product[8].

4.1.2 Uncertainty in field calculations

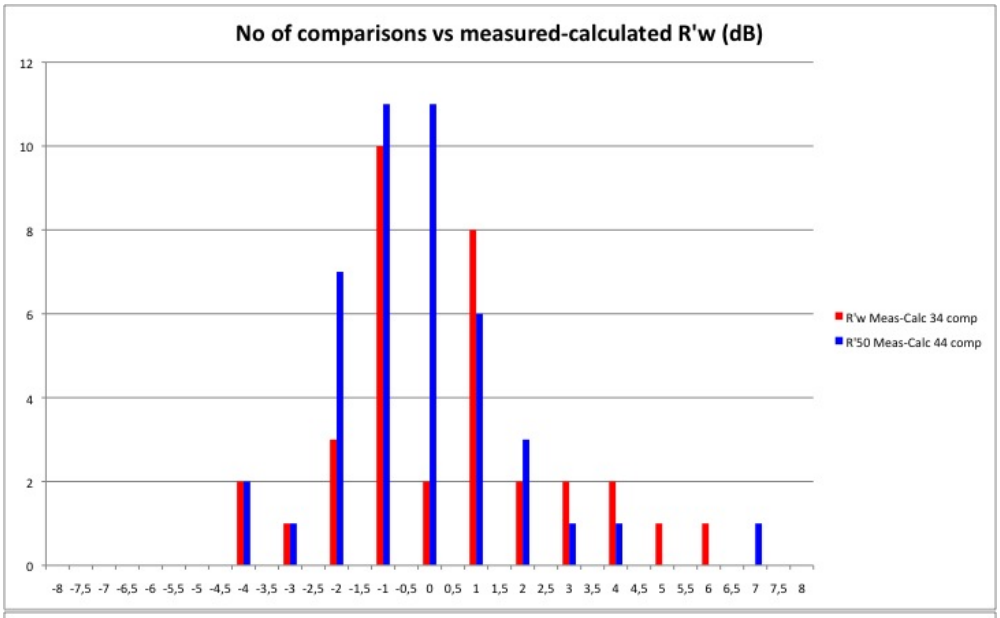
In the same Nordtest project[56], the author also made field calculations of airborne and impact sound insulation for some building cases and compared the results with field measurements (performed by different consultants across the Nordic countries). The calculations were made according to parts 1 and 2 of the EN 12354, using BASTIAN® software and the Nordic databases[27]. The results of the comparisons are tabulated in Table 5, from the paper[57]. All comparisons refer to vertical sound insulation and heavy slabs.

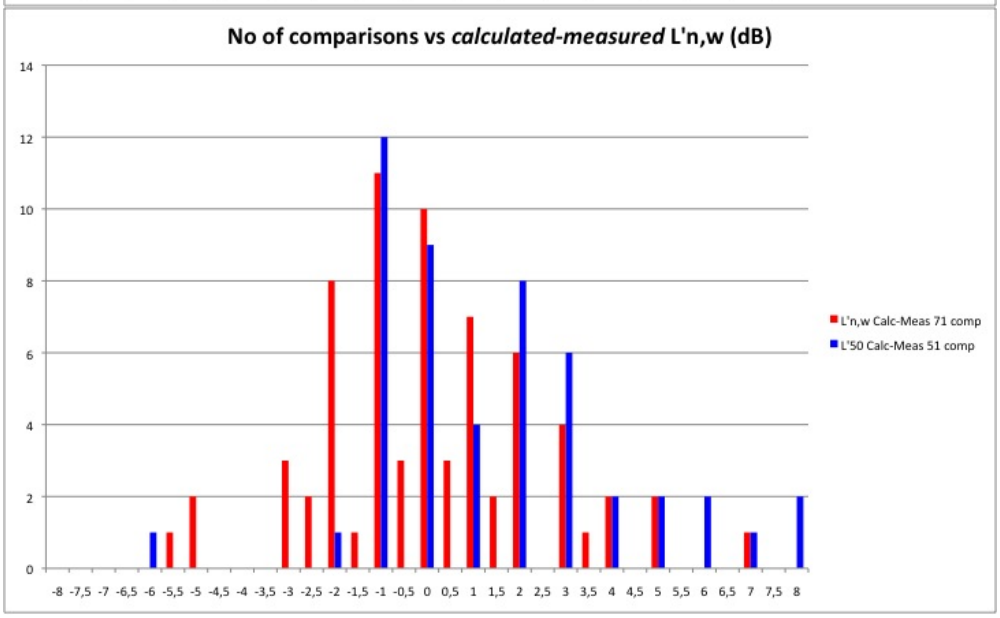
More data have been added to the analyses since publication of the Nordtest report NT tech 603. The values within parentheses were recalculated to include these additional data.

Table 5. Comparison between measured and calculated sound insulation[57] (amended with new data)

Difference calculated-measured insulation, in decibels:	R'_W	$R'_W + C_{50\text{-}3150}$	$L'_{n,W}$	$L'_{n,W} + C_{I,50\text{-}2500}$
…between the averages	-0,17 (-0,29)	0,42 (0,19)	1,87 (0,7)	1,91 (1,7)
…standard deviation	2,3 (2,4)	1,6 (2,0)	4,4 (3,4)	2,9 (3,1)
…90%-confidence limits (5% risk of non-conform.)	**3,5 (3,5)**	**3,0 (3,4)**	**5,1 (4,7)**	**2,7 (3,3)**
Number of comparisons	*26 (34)*	*36 (44)*	*30 (71)*	*43 (51)*
Measured average of sound insulation	*59,4 (58,8)*	*57,6 (57,3)*	*54,1 (50,4)*	*51,3 (51,6)*

The differences in Table 5 have been sorted into 0,5 dB classes and plotted in figures 23a and 23b to illustrate the probability distributions which have been assumed to resemble Gaussian probability density functions in course of preparing the safety margins.



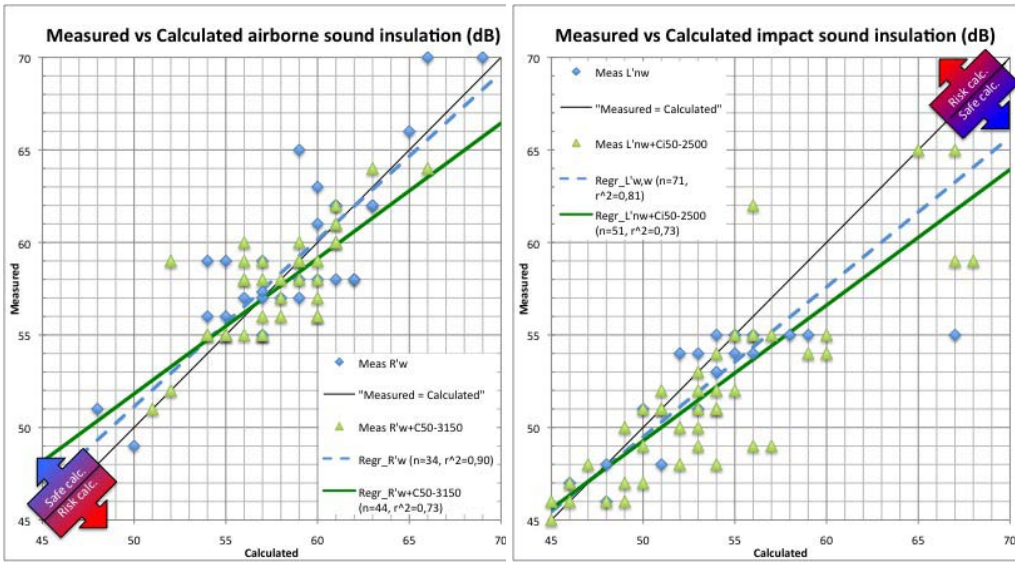


Figures 23a and 23b. a) top; distribution of differences between the calculated and the measured airborne sound reduction indices (R'_w and $R'_w + C_{50\text{-}3150}$). b) bottom; calculated-measured weighted normalized impact sound pressure levels $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$. In both figures, positive differences (x-scale) imply better measured results than calculated.

The average and standard deviation values in Table 5 refer to all differences. Since the standard deviation of the measurement methods appears to be in the order of 1 dB (Table 4), un-

certainty of input data (elements, junctions) and the calculation model seem to dominate the combined uncertainty in Table 5.

Another question that might be of interest is whether there are systematic differences between the predicted and measured values when high or low sound insulation values are compared. For this purpose, regression analyses were also made to find any trend in this direction.



Figures 24a and 24b. Regression analyses of measured vs. calculated sound insulation.
a) left; weighted airborne sound reduction index (R'_w and $R'_w + C_{50\text{-}3150}$).
b) right; weighted normalized impact sound pressure level $L'_{n,w}$ and $L'_{n,w} + C_{I,50\text{-}2500}$

The regressions illustrate a tendency that may have a practical explanation: the higher the requirement and calculated value, the more sensitive the real insulation to errors of workmanship as well as of measurements. During the setup of the calculation model, it may be useful to include more transmission paths and to simulate the effects of deviations in the real constructions on the site, as this serves to identify risks and indicate where greater care must be taken to ensure the expected sound insulation. The regression lines may be uncertain because most data are centred in a narrow range of insulation values that correspond to Swedish building practice. When a few statistical outliers were removed, the correlation coefficient increased and the slopes approached the 45 degree line by a few degrees.

The conclusion from this analysis is that for the purpose of ordinary buildings (and standard requirements), a fixed safety margin may still be more adequate rather than a margin that increases with the expected sound insulation.

On the basis of the results of the Nordtest study, some practical safety margins for users of the software and the databases were estimated for the purpose of predicting the sound insulation of heavy building partitions[ee], with respect to an estimated risk of 5-10% that a field measurements is disapproved. The margins presented in Table 6 have been recommended to consultants for the last 5 years[ff].

[ee] To the knowledge of the author, no comparisons of this kind have been made for lightweight constructions, , except for Pedersens results, c.f. next page.

[ff] To date, the margins in Table 6 have not been questioned which indicates they may be sufficient for most applications (although this indication should not be taken as evidence).

Table 6. Recommended safety margins for calculations of heavy building constructions.

Practical safety margin to a requirement, in decibels	R'_W	$R'_W+C_{50-3150}$	$L'_{n,W}$	$L'_{n,W}+C_{I,50-2500}$
in an individual case, as verified by one sample measurement:	2	3	2	3
as an average of measurements, allowing 2 dB deviation (if the average value conforms with the requirement)	0	1	0	1

The new data do not call for any changes in these recommendations to designers. However, there are some underlying assumptions in the analyses presented in the paper, which should be commented upon:

- The field cases may be considered *representative* of the heavy constructions widely used in Sweden, but suitable margins for other types of constructions may differ.
- The field cases were not *randomly chosen* but merely made available to the author by clients and colleagues in the Nordic countries. Thus, they may be biased for various reasons, e.g. measurements were taken because of complaints about poor sound insulation, or on the contrary, they were selected because they were assumed to perform well. Both reasons would introduce systematic errors into the results, fortunately of opposite signs.
- Any systematic influence of only one operator making all calculations was compensated to some degree by the addition of the *uncertainty of operator* assumptions as discussed in the previous section. This error could lead to an underestimation of the safety margin, compared to the case where several operators are asked for estimates and make different models and choose different input data for the elements and junctions.
- Not all the constructions in the building cases were well *documented* and the author had to make some qualified assumptions, based on what was typical for the type and age of the building, with the help of an architectural survey[29]. This error would exaggerate the safety margin, compared to cases where constructions and workmanship are well documented.
- The probability density function (PDF) of the difference between calculated and measured results was assumed to approximate a Gaussian function. Generally, the central theorem of statistics implies that the PDF of a parameter composed of several parameters (each with its own PDF) tends to follow a Gaussian distribution even if the individual parameters are not normally distributed. Wittstock[10] as well as Mahn and Pearse[59] have demonstrated by means of Monte Carlo simulations that the airborne reduction index (composed by two sound pressure levels and one reverberation term) tends to be normally distributed. Comparisons in round robin tests involve more parameters, which could be expected to increase the convergence of the PDF towards a normal distribution. C.f. Figures 23a and 23b.
- The number of comparisons should be high enough to choose coverage factors from the normal distribution. Coverage factors from the Student-t distribution would be more appropriate, but these are only slightly higher for the same probability and degrees of freedom (>30). This means the given probabilities of failure are slightly underestimated in the tables above.

The results of the Nordtest study were presented at a conference on uncertainty held in Le-Mans 2005[60].

Other researchers have also made comparisons between predicted and measured sound insulation in the field. Pedersen presented some results from his Nordtest study in 1997[25], that inspired the author to continue similar analyses (presented above). About 200 field measurements from the Nordic countries for both heavy and light weight structures were compared by Pedersen with calculations according parts 1 and 2 of the EN 12354. The main findings are concluded in the Tables 7 and 8 below.

Table 7. Average, standard deviation and 90% confidence limits for the difference between calculated and measured R'_w-values.

	Direction of transm.	Average	St. dev.	90% conf. limits
Monolithic basic constructions	Horizontally (walls)	0.2 dB	1.9 dB	± 3.4 dB
	Vertically (floors)	0.4 dB	2.6 dB	± 4.5 dB
Lightweight double constructions	Horizontally (walls)	0.1 dB	3.1 dB	± 5.3 dB
	Vertically (floors)	0.4 dB	3.2 dB	± 5.5 dB

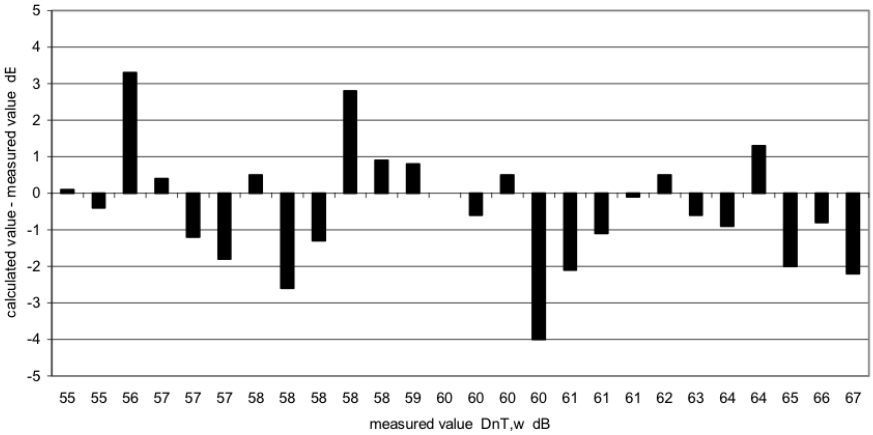
Table 8. Average, standard deviation and 90% confidence limits for the difference between calculated and measured $L'_{n,w}$-values vertically.

	Average	St. dev.	90% conf. limits
Monolithic basic constructions	-0.5 dB	3.1 dB	± 5.2 dB
Lightweight double constructions	0.0 dB	5.4 dB	± 9.1 dB

Lang presented an extensive comparison between 60 field measurements and calculated values at the inter-noise in Nice 2000[61]: Lang made this observation: "*The compliance of measured and calculated DnT,w – values was very good. On average the difference calculated value – measured value was –0,4 dB for adjacent rooms and 0,3 dB for rooms one above the other (details on the results see fig.5). All calculations were carried out with the simplified model (calculation with the single number quantities only).*"

According to a presentation at the Euronoise conference in 2009, no updates have been made to these results and they are still considered relevant for Austrian concrete buildings. Figure 25 from Lang's report (*in German*) illustrate the difference for the 60 buildings that were included in the comparison. However, this comparison cannot be considered valid for other types of building constructions since the flanking transmission by the outer wall was assumed to dominate the overall transmission. A 3 dB margin appear to be appropriate for these constructions as very few cases exceeded this difference. Langs study indicate a similar tendency as was discussed above, where the calculated insulation is higher than the measured for cases with high sound insulation values.

Figure 9: Difference calculated value – measured value for measurements between rooms side by side



Source: Lang, 2001

Figure 10: Difference calculated value – measured value for measurements between rooms one on top of the other

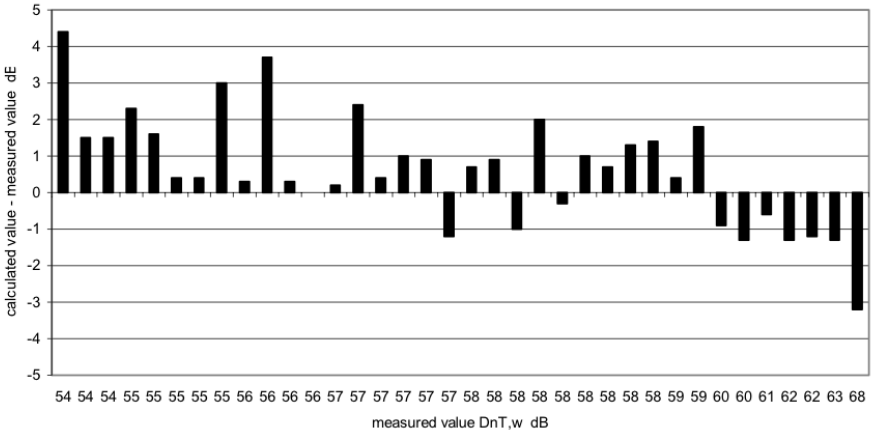


Figure 25. Difference between the calculated and the measured $D_{nT,w}$ -values. From Lang[61].

Galbrun analyzed airborne sound transmission between adjacent rooms divided by masonry walls by comparing results obtained from the EN 12354-1 with SEA predictions as well as measurements. Galbrun wrote: "*it is shown that the restriction of the Standard to first-order flanking paths can lead to large errors in predictions when compared to measurements and SEA results taking into account all transmission paths*." [62]. This problem would be worthwhile looking closer to, something that remains to be done.

Crispin, Ingelaere and Wuyts presented measurements and calculations of lightweight cavity walls at the Acoustics 08 congress in Paris[63]. For rigid junctions, the vibration reduction index of the junctions agreed well with the EN 12354-1 model. They presented an extended model of the EN 12354-1 for walls with cavities and resilient junctions.

Martin et al presented *in situ* measurements of vibration attenuation between solid building elements at the internoise 2004[64]. Their paper also provides a brief theoretical background.

Ruff and Fischer presented results on vibration reduction at junctions and measured flanking transmission at Acoustics 08[65].They concluded that: "*It is difficult to consider decoupled flanking gypsum walls exactly because of the missing input data. The calculation with singular values*

according the simplified model of the EN 12354-1 and the measured vibration reduction indexes of the gypsum walls as input data has shown a comparative good correlation to the actually measured sound reduction index."

Wittstock presented some uncertainty estimates in the field insulation estimates in a recent web-based article[66]: "*A new approach for calculating the measurement uncertainty made it possible for the first time to realistically evaluate the uncertainties of building acoustic predictions according to EN 12354-1 from the uncertainty contributions of the acoustic input quantities…. The starting point was the fact that the sound insulation results from a total of 31 acoustic quantities in this case. An individual uncertainty is associated with each of these quantities. Then the uncertainty of the predicted sound insulation is yielded from the uncorrelated superposition of the single uncertainties weighted by the appropriate sensitivity coefficients… The results of the spreadsheet turned out to be consistent with other independent prediction results. Furthermore, 24 real building situations have been considered. It could be shown, that the deviations between measurement and prediction results can be explained essentially by the uncertainties (Figure 26). This has created a high level of transparency in the prediction and has thus considerably increased the acceptance by the users in practice.*"

Figure 26 from this article[66] provides an informative overview of the uncertainties:

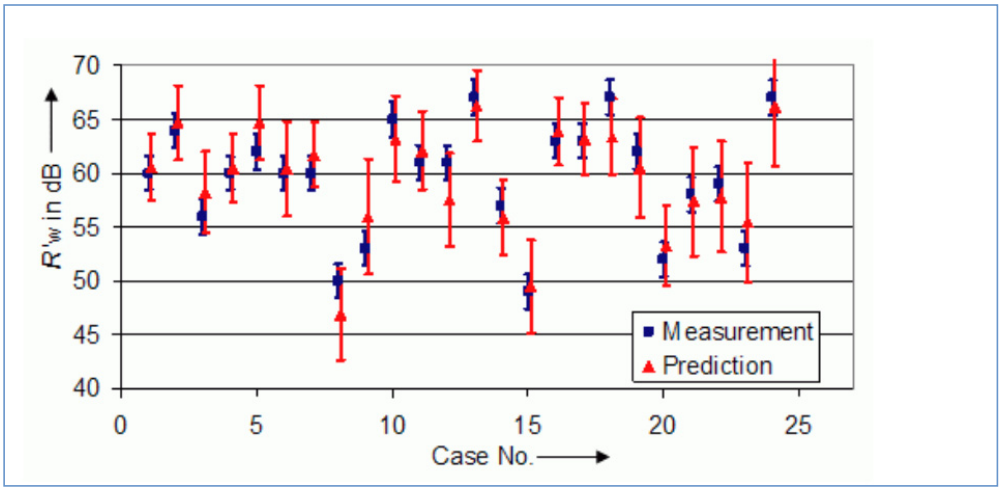


Figure 26. Comparison between measurement and prediction results corresponding to 95%-confidence intervals. From Wittstock[66]. The predicted uncertainty is computed from uncertainty estimates of the building elements and junctions used in each case. The field measurement uncertainty is estimated from one global value (ISO/WD 140-2).

4.1.3 New field measurements compared to the EN 12354-2 in apartment buildings

The comparison discussed in section 4.1.2 also covered impact sound, but the number of cases in the Nordtest round robin test[56] was less than optimal for the purpose of estimating the magnitude of uncertainty in field measurements. Lang's survey[61] had revealed poor agreement between calculations and measurements of impact sound, for which there was no obvious reason presented. Since floating floors were used, it might be worthwhile to examine whether stiff contact points are made between the floor and the concrete slab or walls, which are common when the workmanship is not very well controlled (according to experienced consultants). Figures 27 and 28 indicate floating floors perform worse in the field than expected from results under well controlled workmanship in the laboratory.

Later studies conducted by the author yielded new estimates of the impact sound insulation[67 68] on the basis of measurement data from 40 Finnish apartment buildings. All of these buildings have heavy slabs and exterior walls that were well documented. The measurements

were made by the same operator using the same equipment[gg]. The uncertainty of calculations was compared to measurements and a margin was computed as a 10% risk of exceeding the required impact sound pressure level in the field. This risk was calculated as the average difference increased by 1,28 times the standard deviation of the differences. As can be seen from the Figure 27, it is well below the general (recommended) safety margin of 3 dB.

However, the deviations at high frequencies are systematically greater than expected, as is indicated by the bold black line in Figure 27 taken from the report[67] (and the article[68]).

Hardening of a soft flooring underlayers may be one reason for the discrepancy at high frequencies, since the input data for the calculations are based on laboratory measurements of sample of products that have not been aged. The constructions with floating floors performed much worse than expected at medium and high frequencies, with respect to both the average and the standard deviation. The performance at high frequencies affects the weighted $L'_{n,w}$ values more than the $L'_{n,w} + C_{I,50\text{-}2500}$ values (as defined in ISO 717-2).

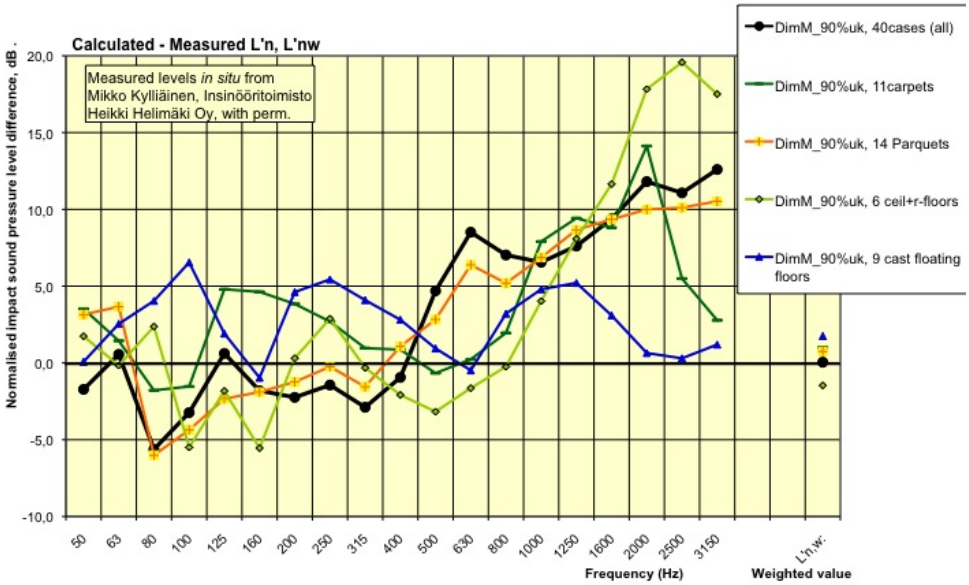
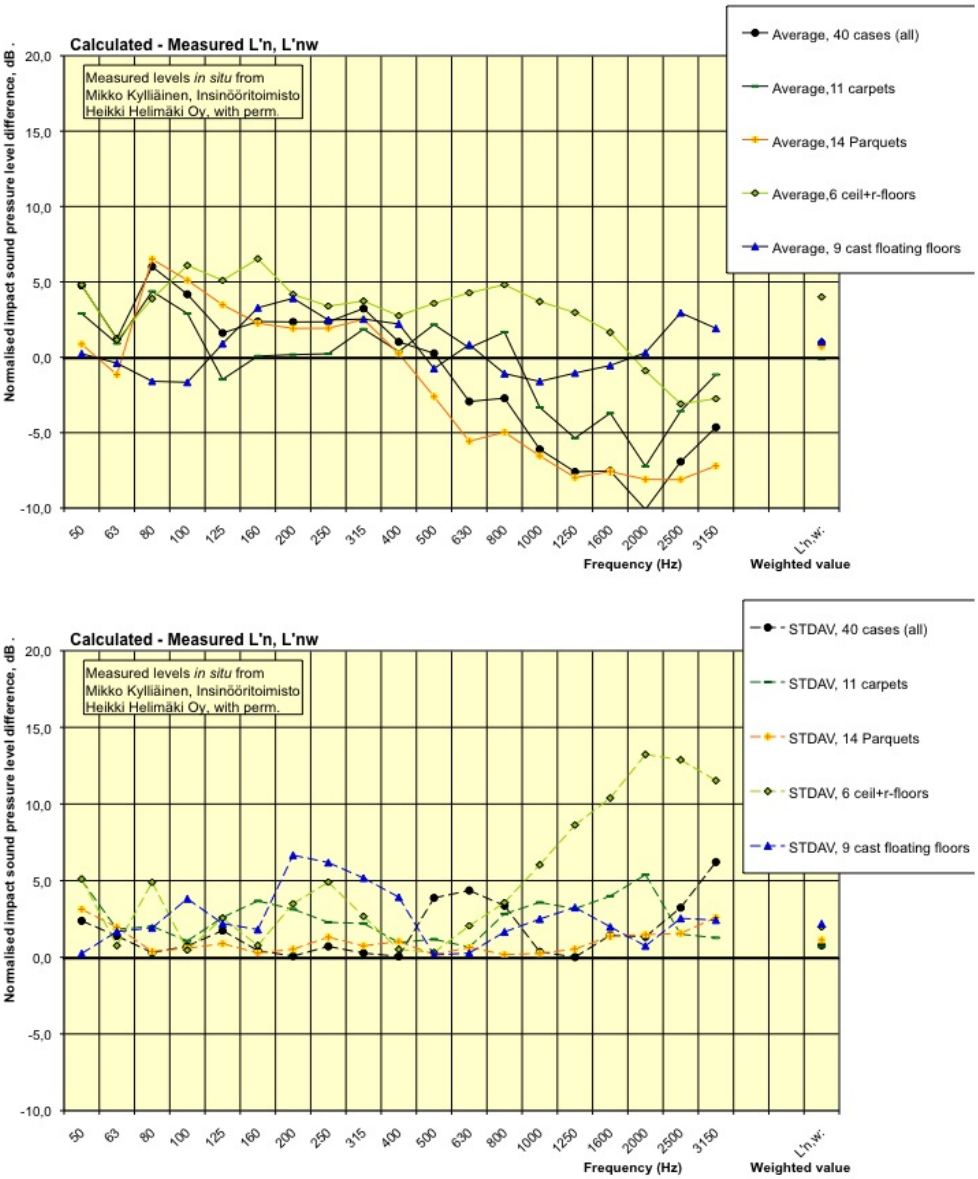


Figure 27 (top). Difference between calculated and measured impact sound pressure levels, plotted as a margin. The margin is calculated as the average deviation increased by 1,28 times the standard deviation in each frequency band 50-3150 Hz and as for the weighted single numbers. From ref. 68.

The average differences and their standard deviations used in Figure 27 are given by Figures 28a and 28b.

[gg] The data were measured and made available to the author by Mikko Kylläinen at Heikki Helimäki Acoustic Consultants, who is gratefully acknowledged. These data were included in the analyses presented in section 4.1.2.



Figures 28a and 28b. Difference between calculated and measured impact sound pressure levels. a) top; the average deviation, b) bottom; the standard deviation in each frequency band 50-3150 Hz and for the weighted single numbers. From ref. 68.

4.2 Airborne sound from service equipment

4.2.1 Calculation methods

The prediction of airborne sound from air handling equipment has been described in part 5 of EN 12354 (approved in 2009). To the knowledge of the author, systematic comparisons between calculations according to this standard and measurements in the field (in order to esti-

mate the uncertainty) have not yet been made, but practical experience with similar methods indicate satisfactory uncertainty. The measured room average A-weighted sound pressure level is typically within 3 dB of the calculated value, except where sound at low frequencies dominates the spectrum. Higher levels may occur where the flow is disturbed by sharp bends or obstacles in the air handling equipment, or in long ducts without branches,. An important factor for the estimation of the accuracy of the calculation method is the accuracy of the field measurement method used to 'verify' the calculations. To enable meaningful comparisons the measurement accuracy must be known.

4.2.2 Field measurement methods

Field measurements of sound pressure levels can be performed according to the EN ISO 16032 standard (engineering grade) or the EN ISO 10052 standard (survey grade). The microphone positions prescribed by these standards are to some extent formulated on the basis of results from a Nordtest project conducted by the author in 1996-1997[69]. The background of this project was the need to find a method that reduces the large uncertainty of the room average sound pressure levels at low frequencies as are typically encountered when the existing methods were applied.

The Swedish National Board of Health and Welfare issued recommendations for the restriction of sound at very low frequencies (31-200 Hz) in dwellings[70], and commissioned SP (i.e. the author)[hh] to develop a measurement method for the verification of such sounds[71].

In order to develop a measurement procedure that would reduce the scatter of the spatial average sound pressure level, a survey was conducted in various types of room exposed to low frequency sound from an artificial source, where a shaped spectrum was kept at a constant level, including tonal components in some third octave bands from 31 Hz-200 Hz.

Sound pressure levels were measured in a dense mesh of positions in 10 rooms/cases, both in reverberation rooms and in the field, under realistic conditions. The spatial variation of sound pressure levels in realistic rooms turned out to be very complicated and deviated considerably from the idealized mode shapes of regular shoebox room modal models under the assumption of completely rigid boundaries. For instance, it was found that the sound pressure levels in the corners differed a great deal from each other. The distribution of sound pressure levels was more even in spaces with more sound absorption and light building materials compared to rooms with heavy materials and a low degree of diffusing furniture etc. On the basis of these empirical data, 24 existing measurement methods (from industry standards, guidelines, regulations etc.) were evaluated by a Monte Carlo technique, where the restrictions of each method were applied to exclude invalid results. From each set of simulated measurement results, the standard deviation of uncertainty and the average deviation from the average of all acceptable measurement positions in each room were calculated to characterize the performance of this method.

The advantage of this approach was that no time variations in sound pressure levels were introduced which would have been a risk had physical measurements been undertaken. This approach also enabled a large set of simulated measurement results to be established for each of the 24 methods tested. The same number of physical measurements with each method would have been unfeasible but the simulations were an efficient means of obtaining enough data to make analyses of the uncertainties. All methods could then be compared on the same premises. This approach may be regarded as "situation B" tests in accordance with the draft ISO/WD 140-2, i.e. a few test objects are fixed but measurements are repeated many times. The main results were published in Acta Acustica in 1999[72]. Two observations from this study have practical implications that may be worthwhile mentioning:

- Most methods described in industry standards, guidelines etc tend to underestimate the room average sound pressure level at low frequencies, i.e. they introduce systematic errors compared to the room average. If the sound pressure levels close to the walls are considered

[hh] Work performed at SP Technical Research Institute of Sweden 1995-1996.

more important (from a subjective point of view), the systematic error is even more pronounced

- The uncertainty of the measured room average (random errors) was large for most of the methods, but may be reduced considerably by increasing the spatial averaging or including a specific corner position

The first observation, as illustrated by the Figure 29a from the Nordtest report, was presented at a conference on low frequency sounds[73] where the standardized A-weighting of sound pressure levels in frequency bands was discussed with respect to its ability to predict the perceived disturbance of low frequency sound. It i a common opinion that the A-weighted sound pressure level underestimate the subjective annoyance with sounds and this should be explained by the shape of the A-weighting filter, but this can to some degree be related to the systematic underestimation of the sound level closer to the walls, as mentioned above.

The second observation, as illustrated by Figure 29b, was used to define a principle for the measurement procedure, which could later be integrated with the EN ISO 16032 and 10052 standards. The procedure involves measuring the sound pressure levels in all corners and only including the corner of the room having the highest C-weighted level. The measurement in one corner is added to two measurements in the middle of the room (i.e. an average of the three positions is the final result). Although somewhat cumbersome to perform in practice, the procedure reduced the uncertainty considerably (see Figures 29, curves denoted SS-63_Cfix) compared to other methods using 1-3 positions. Procedures using 6-10 microphone positions, e.g. ISO 140, yield comparable uncertainties but may take longer to perform, in particular when the sound varies over time. The procedure suggested to be included in the ISO 16032 and ISO 10052 reduces the standard deviation at very low frequencies from about 4 dB (from older methods) to approximately 1 dB (the new methods). Other researchers, e.g. S. Pedersen et al, have compared alternative methods to these standards in order to reduce measurement uncertainty even further[74]. For the measurement of airborne sound insulation, a new routine was proposed in the annex H of the SS 25267, where an extensive scanning procedure is described.

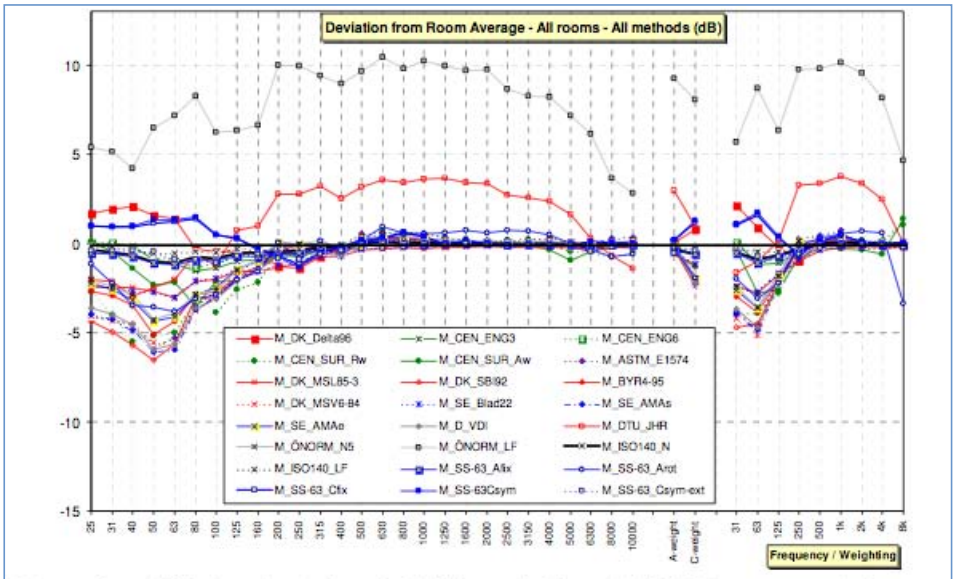
Hopkins suggested at a COST work group meeting in Växjö in 2009, that the “corner method” might also be worthwhile considering in the field methods for sound insulation, if they were extended to include very low frequencies (down to 20-25 Hz has been discussed). An alternative would be to increase the number of microphone positions even further, e.g. with 10 positions in each room. However, these suggestions remain to be tested. How to determine the reverberation times at low frequencies also remain to be examined. Hopkins presented new results[75] at the Euronoise 2009, based on analytical expressions where various techniques have been applied to measure the room average[ii].

Bodlund made theoretical calculations and measurements to determine the statistical confidence intervals of spatial and time averaged sound pressure levels and reverberation times in reverberation chambers, typically used in building acoustic laboratories[76]. Bodlund also applied some advanced expressions published by Waterhouse in 1968 and by Lubman in 1968-1971.

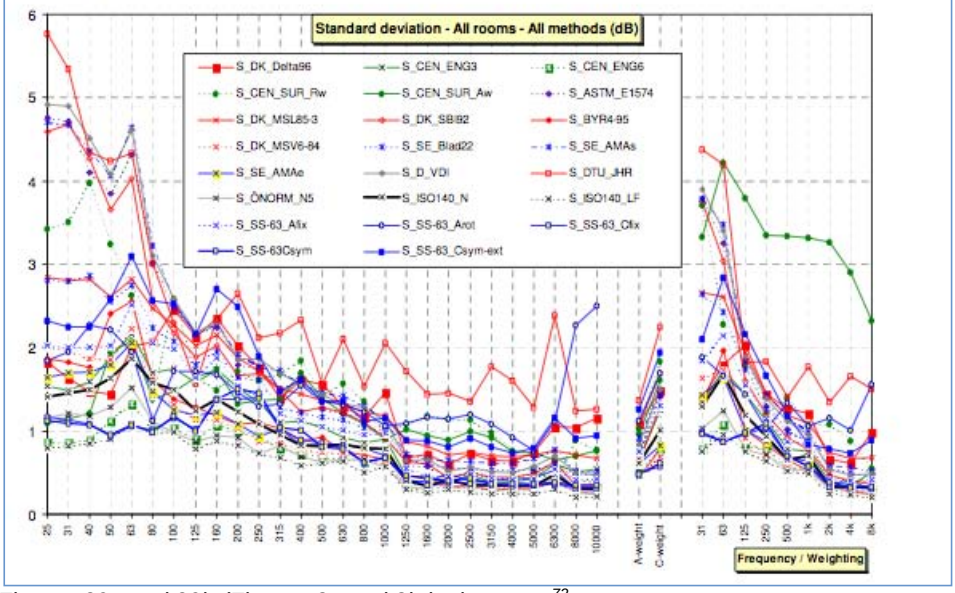
Olesen made theoretical calculations of the spatial variations of sound pressure levels (and reverberation times) in rooms and compared these to measurements. He published the results in a Nordtest report[18] that also includes recommendations on non-idealized measurement situations in the field. These recommendations were published in another Nordtest-report (NT Tech 203) and are to some extent included in the ISO 140-14 standard.

Bethke and Wittstock described general uncertainties in the methods for measuring sound pressure levels in a hemianechoic room[77], and the application of the ISO guide GUM[16].

[ii] These new results have not yet been compared to the results obtained by this author. At a quick glance they appear to agree to some extent.



Figures 3a and 3b. Overview. The embedded legend refers to Table 2. Frequency axis show third octave bands 25 Hz - 10 kHz, A- och C-weighted, octave bands 31 Hz - 8 kHz. (a) Top: Ensemble mean deviation from room averages (dB) calculated by simulating the measurement methods. (b) Bottom: The mean standard deviation. The measurements were made in the 10 rooms according to Table 1. The result graphs are also presented in smaller groups below and in the Appendix C.



Figures 29a and 29b (Figures 3a and 3b in the paper[72]). Overview of the simulation results for 24 measurement methods. The ISO 140-3 standardized method for the 100-3150 Hz frequency range is plotted as a reference indicated by a bold black and crossed line. a) top; deviation from the room average, b) bottom; standard deviations.

4.2.3 Sound from radiator valves

Sound from radiator valves may be a problem if the pressure loss and flow through the valve and the heater is too high. A measurement method for the determination of sound power from radiator valves was adopted as a Nordtest method NT ACOU 101 in 1996[78]. During the development of this method, the uncertainty issue was the most difficult to solve. The repeatability of consecutive measurements was good, but when the valve was removed and remounted, the sound power changed dramatically in frequency bands as well as in the A-weighted value. After some practical experiments had been performed it turned out that the main factor governing the sound emission was the amount of air dissolved in the water. A vacuum pumping procedure solved this problem and made the repeatability much more stable. It was also considered correct also from the perspective that the operating conditions of the test circulation system would then resemble the long-term condition of a realistic system in a building, where the dissolved air diminishes over time. This study serves as an example of that refining the laboratory routines can help reducing the uncertainty.

4.3 Reverberation time in rooms

Part 6 of the EN 12354 standard was approved in 2003 and used to change the Swedish sound classification standard SS 25268[20] in terms of the type of requirement in premises for health care, education etc. The focus was then shifted from the measured reverberation time to sound absorption area of the room. In the course of preparing this second edition of the standard several types of applied studies were made, mainly in classrooms. Larsson performed measurements[79] in a special laboratory that was intended to resemble a classroom, an office and a meeting room under ordinary field conditions. The results were rather confusing at first sight, since the reverberation times did not fit well with the predicted values. In fact, the results were almost independent of the type of sound absorber used (class A, B and C according to ISO 11654). The reason suggested was wall reflections that prolonged the measured reverberation times more than was initially anticipated by the laboratory. An important practical result of this study was the amendment of the SS 25268 by the addition of recommendations about the shape and furniture of classrooms and similar spaces for speech communication.

The author performed another study that helped implement the use of EN 12354-6 in the new edition of SS 25268. Measured reverberation times from 44 classrooms were compared with values calculated according to the basic method of the EN 12354-6 standard. Figures 30 and 31 from the Euronoise paper[80] present the results of the comparisons.

Both porous absorbers and perforated plasterboard absorbers were analyzed, since previous studies indicated that they might behave quite differently *in situ* than in the laboratory.

Systematic and random differences between the calculated and measured reverberation times were derived. Practical safety margins were derived from these differences which should be observed when the type and amount of sound absorbers are determined.

The resulting “safety margin” was deduced from Figures 30a and 30b. The systematic difference (mean deviation between calculated and measured reverberation times) is first subtracted from the calculated value. To correct for the scatter of data, the calculated value is also increased by the standard deviation multiplied by a statistical coverage factor of 1,28, which was assumed to correspond to a 90% probability of compliance with the required value, i.e. a 10% “risk” provided that the room and furniture is of the same types as in the rooms used in the study.

Figure 30c presents the sum of negative mean deviation terms (from fig. 1) increased by 1,28 times the standard deviations, i.e. the safety margins. They turned out to agree well with recommendations issued in the Danish regulations, where the same tolerances were included[81].

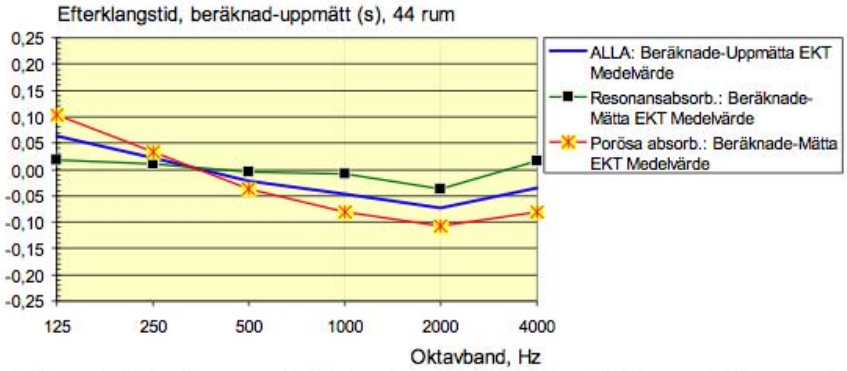


Fig. 1. Mean deviation between calculated and measured reverberation times, s. (44 spaces). Legend: "Efterklangstid"-reverberation time", "beräknad"-calculated, "uppmätt"-measured, "ALLA"-all 44 cases studied, "Resonansabsorb."-resonant tiles (21 cases), "Porösa absorb."-porous tiles (23 cases)

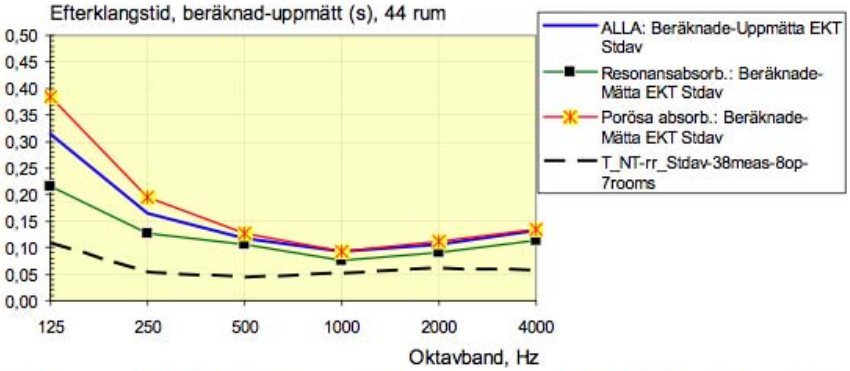


Fig. 2. Standard deviation between calculated and measured reverberation times, s. (44 spaces). Legend, see fig. 1. The line "T_NT-rr"-estimate of reproducibility of the measurement method [4].

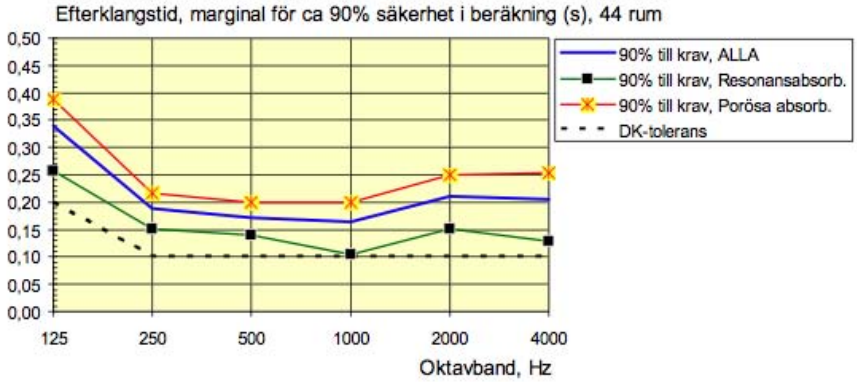


Fig. 3. Sum of negative mean deviation (fig. 1) and 1,28 times the standard deviation (fig. 2) between calculated and measured reverberation times, s. Legend, see fig. 1.

Figures 30a, 30b and 30c (Figures 1-3 from the paper[80]). Differences between calculated and measured reverberation times in the field. DK-tolerans cited from the Danish guidelines[81].

However, some of the rooms used in the study were not well documented. A selection of 23 rooms with diffusing furniture and documented sound absorbers were selected for a new analysis, and Figure 31 (Figure 4 from the paper) illustrated a reduced need for a safety margin.

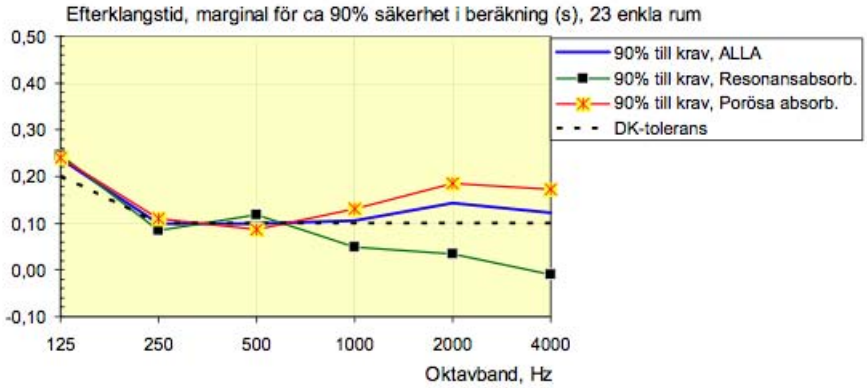


Figure 31. Sum of negative average deviation and 1,28 times the standard deviation between calculated and measured reverberation times, in seconds. 23 field cases with diffusing elements have been selected from the 44 cases. Legend, c.f. Figures 30. From ref. 80.

The SS 25268 requirement was finally expressed so that it included 0,1 s tolerance in the 250-4000 Hz octave bands and 0,2 s in the 125 Hz octave band.

It should be mentioned, that for the last case (Figure 31), the coverage factor should have been selected from the Student t-distribution to compensate for the fewer cases analyzed. Thus, it should have been 1.32 rather than 1,28. However, this error does not change the magnitude of the margin.

5 Responsibility of the participants of the building process

5.1 Application of the Swedish requirements

For several reasons the Swedish building process has become more complicated to manage with respect to acoustic issues. If this process is well understood the uncertainty in the final acoustical performance of the building can be reduced.

As in many countries, new buildings are often erected at complicated locations inside city centers and hence often exposed to high sound levels and ground vibrations from various types of traffic. High demands on sound insulation between various types of interior spaces are frequent, e.g. between residential apartments and premises for commercial activities.

Furthermore, new architecture, new building products and new structural systems are frequently suggested (by the designer, the contractor or a manufacturer), that place challenging demands on the designer for accurate predictions of the acoustic properties of the building. This is pronounced when empirical experience is not available for such specific applications.

The sound requirements used in Sweden are described in two national sound classification standards (SS 25267, SS 25268), see section 2.4. These standards are revised continuously by a standing committee (TK 197) one of the main tasks of which is to resolve interpretation and application problems and to revise the standards whenever new applications or problems arise. Furthermore, the committee maintains a web page with frequently asked questions and answers[82]. All of this work serves the common purpose of reducing uncertainty with respect to interpretations and applications of the standards.

In the latest edition of SS 25268 issued in October 2007, the users of the standard are even encouraged to amend its conditions with specific definitions in order to optimize the outline of the building with reference to its intended use. They can still claim to conform with the stated sound class, if they present documentation that explains why the specific exception or alteration of the requirement set out in the standard is still within the general quality scope of the relevant sound class. The purpose of this option is to help developers and contractors minimize building costs for constructions that do not improve the acoustical climate of spaces within the building. Whether or not this concept increases the uncertainty of the application of the standard will be revealed in the future.

The SS 25267 and SS 25268 standards are based on performance, i.e. they specify sound conditions of various spaces within the completed building in great detail, but still leave the choice of technical solutions open for domestic as well as foreign suppliers. This system may be considered an open one, compared to the type of requirements used in some other countries, where it is customary to refer to approved constructions, e.g. the German industry standard DIN 4109[83] and the Robust Details system used in England and Wales (partly also in Scotland)[84]. As foreseen by the Swedish authorities, there are now an increasing number of innovative products and structural elements, also from foreign suppliers, that could be combined in order to meet the requirements stated by the client, the national building codes or the standards. In a small market as in Sweden, this has been beneficial.

However, there are disadvantages with the open/performance based requirements as they imply that the client and other parties involved in the building process interpret the rules and make appropriate decisions within each project, which is one reason behind the need for continuous revision of the sound classification standards, as discussed above.

The EN 12354 standard and a group of laboratory test methods may help our acousticians make rational choices and decisions related to combining products. This issue was dis-

cussed into some detail in section 1, but the following descriptions illustrate the broader context of decision-making during the building process.

It may be concluded from experiences in Norway, Germany and the United Kingdom, that it may be preferred to maintain both methods concurrently. Approved solutions for each sound class that yield a large margin to the requirements may be preferred by those who do not want to optimize their constructions. For other parties it may be preferred to choose constructions and building products carefully with the help of calculations and databases of the performance of each product in accordance with laboratory methods. In the UK, about half the new residential buildings employ constructions approved by the Robust Detail Ltd, the others choose so called precompletion tests on the site before finalizing the building projects.

5.2 The”Bullerskydd i bostäder och lokaler” handbook

The organization of the building industry differs from that of manufacturing industry. Architects, planners, technical consultants, manufacturers of building products and contractors assemble teams that cooperate within individual building projects. With each new project, new people meet in project groups to assign tasks and solve common problems. The project development (design) is often managed by a project leader on behalf of the commissioner, who may be a developer (also referred to as a commissioner) or the contractor (who builds the house). The architect may play a leading role, but it is not unusual in Sweden that he (or she) is only commissioned as a consultant who reports to the project leader. This kind of temporary organization has been a subject of debate for many years but has turned out to be difficult to replace. The main criticism has focused on unclear responsibilities and suboptimal decisions (the parties do not account for the global result). Sound issues are difficult to manage in this kind of temporary organization, *hence the need to discuss this topic in the context of uncertainty*.

The decision process related to sound issues can be complicated in even an ordinary building project, e.g. for a block of apartments. General requirements must be interpreted with reference to the specific conditions of the project. Sound issues affect many building constructions. Many parties must handle these issues during several phases of the building process. Typical errors and misinterpretations stem from building design (floor plans), product design (input data), calculation models (assumptions), workmanship and uncertainties in field measurements.

Hagberg and the author were commissioned by the National Board of Housing Building and Planning (Boverket) to write a handbook with the title “Bullerskydd i bostäder och lokaler” [85] [jj]. The purpose of this handbook is to facilitate the management of building projects in terms of acoustic issues. This means reducing the uncertainty due to poor cooperation between the parties, interpretation problems etc. The handbook is written in Swedish, but a paper that summarizes it has been submitted to the journal of Building Acoustics[86]. The paper is appended to this thesis.

The Swedish building industry and the local building authorities could use the new handbook to

- Describe how the commissioner (e.g. the developer, proprietor, contractor) can specify the responsibility of each party involved in the building process. Each party may then be assigned dedicated targets, which facilitates the handling of acoustical issues
- Provide interpretations and examples of application of the Swedish sound classification standards, based on a large number of real world questions and detailed examples from the building industry
- Complement other guidelines from the National Board of Housing Building and Planning to facilitate the handling at the local authorities, e.g. of building permits and town planning issues.

The handbook consists of seven sections:

[jj] The Swedish title means “Noise prevention of dwellings and commersial premises”

Sections 1 and 2 are intended for all participants in the building process who may come into contact with acoustic issues, for example property developers, authorities, designers, manufacturers, building contractors, experts and quality assurance managers. These sections provide general background information and a description of *which* party should take *what* responsibility and *when*, during the building process. Figure 32 illustrates the transfer of information between the actors during a building project.

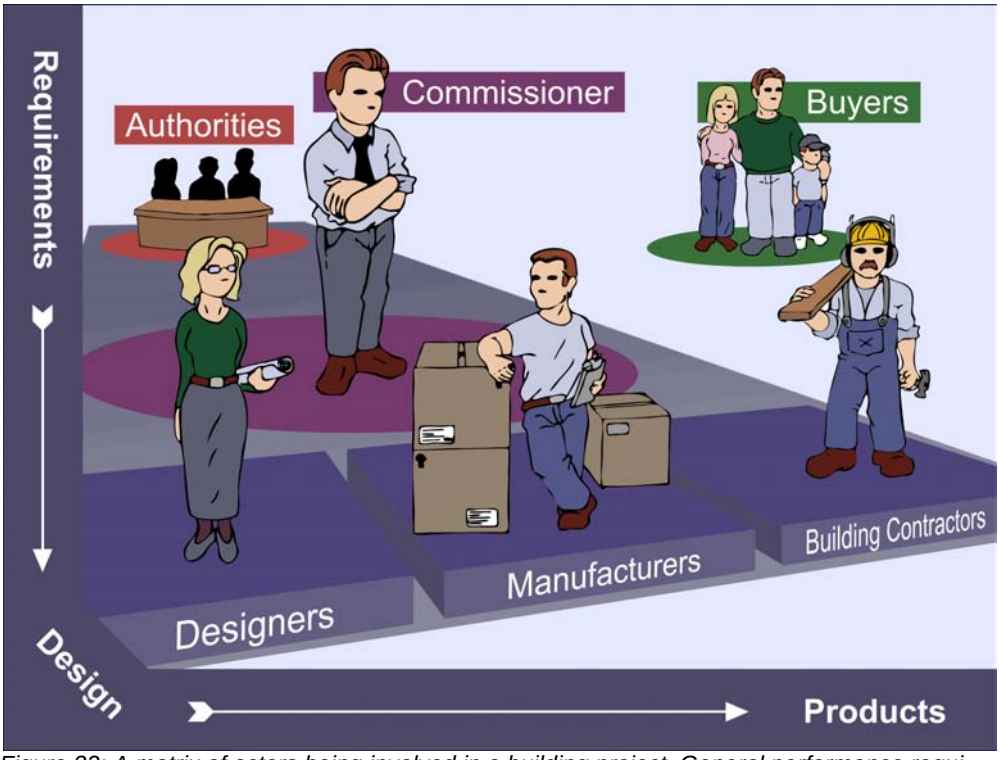


Figure 32: A matrix of actors being involved in a building project. General performance requirements (sound class in situ) stated by the Authorities and the Commissioner must be converted by a Designer to available constructions and products. The Manufacturers must present correct input data to the Designer. The Contractor must follow all instructions carefully and avoid risk constructions. The final Buyers or inhabitants are often not involved during the investment, design and building phases. A poor sound class will reduce the return on investment.

Section 3 recommends the commissioner to engage an acoustic expert to monitor all phases of the project, i.e. the design, drawings, building work at the site as well as the verification measurements in the finalized building. As a result, an *acoustic documentation* will be assembled throughout the project. This documentation is a living document that helps the rest of project team to take the right decisions at various stages of the development.

Section 4 is primarily intended for acousticians as it provides details about risks and interpretational aspects of the sound requirements.

Section 5 informes manufacturers about how they should test and present the acoustical technical properties of their products, as well as provide information that ensures that the product fits connecting structures, handling issues etc.

Section 6 gives general advice to building contractors. The advice involves mounting conditions and risks that should be considered. In many projects, extraneous costs are due to flaws in the drawings and poor workmanship during erection of the building.

Section 7 clarifies some aspects on the verification of the acoustic performance of the building. It has become clear that the international standards for sound testing at the sites (ISO 140-series) would benefit from some complementary instructions to minimize arbitrary choices of measurement locations etc.

The handbook does not cover all conceivable practical problems, nor does it provide any review of theoretical acoustics. However, it contains references to some well-known books and papers that describe theory in greater detail.

5.3 Assigning responsibility by means of EN 12354

The EN 12354 standards may help the commissioner to assign responsibility for the overall acoustic performance of the building, in particular for choosing appropriate products (constructions) and defining adequate interfaces of the products as illustrated by Figure 33.

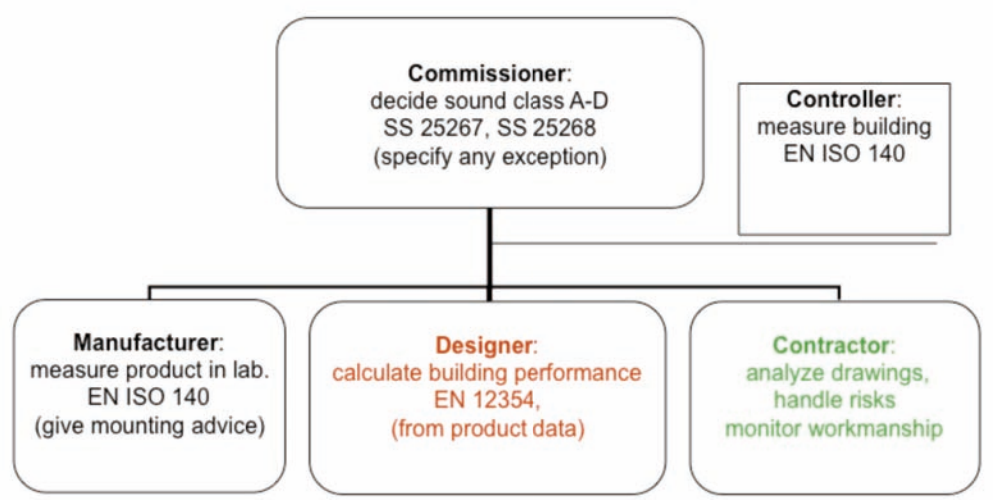


Figure 33. Assigning responsibilities with the aid of EN 12354. The Designer chooses optimal solutions (products) for the building. The Manufacturer documents the performance of his/her products and their effect on other building products. The Contractor analyzes risks and controls the workmanship. The Commissioner defines unambiguous requirements. The Controller makes precise measurements in the completed building.

All parties in this scheme may help to reduce the global uncertainty within their field of work:

- ***The Commissioner*** should state precise requirements and means of verifying performance, for the reasons discussed in the previous sections. He/She can refer to standards, official codes or his/her own experience. Standardized questionaires may help to structure subjective opinions and attitudes among inhabitants and users of existing buildings, thus providing important feedback and input for new building projects. ISO/TS 15666 may be a helpful guideline for outlining such questionaires, since a common structure of the questions and answers enables researchers to compare results from many studies.
- ***The Designer*** can choose robust products (constructions) and carefully define interfaces with other constructions, e.g. to minimize risks of air leakages, flanking transmission or structural

bridges. Appropriate use of lightweight walls and long span slabs can for instance improve the sound insulation due to increased structural losses. During calculations, he/she should keep appropriate safety margins to the required values (as verified by measurements in the completed building). In the Robust Details scheme[84]; products must pass 30 field measurements in order to be accepted in the catalogue of approved details. In the open Swedish system, laboratory results may be accepted without empirical experience of the product, but in such cases safety margins and verification efforts should be increased. This topic is discussed in earlier sections of this thesis.

- ***The Manufacturer*** is assumed to provide the designer with adequate data for the products, to enable calculations of the assembled building in accordance with the EN 12354. The manufacturer should also be responsible for monitoring the performance of the product(s) in the field, since he/she may be the only party who applies the same product in a variety of situations. The instructions on how to use and mount the product may play a vital role when it comes to uncertainty. Building products must be fit for the purpose for which they are intended; they should not be sensitive to the conditions at the building site (temperature, moisture, handling etc). If such products cannot be avoided, the risks should be clearly identified and communicated.
- ***The Contractor*** should analyze the assembly of constructions and identify risks during all phases of handling at the building site. Where workmanship is critical for the overall function, relevant education of workers is recommended and should take place in close cooperation with the designer, the manufacturer and the acoustician.
- ***The Controller*** can contribute general experience when problems may occur, in addition to carrying out precise measurements in the building. According to the third edition of the SS 25267, the controller may use calculations to verify the performance of a building provided that the input data have proven relevant to the constructions herein and the workmanship is under control. The purpose here was to emphasize verification during an early phase of a project as an alternative to the traditional control at a late stage, by means of field measurements. However, there were several objections to this option in the standard, and in 2007, the fellow standard SS 25268 (for public premises) stressed a three step verification of a building:
  - by calculation, that the constructions in the authorized drawings can provide the intended performance at an acceptable risk of failure,
  - by visual inspections at the building site, that workmanship and products conform with the intended construction details
  - by field measurements, that the performance of the building conform with the requirements.

The handbook provides some details of this scheme as well as some instructions pertaining to field measurements, based on supervision of operators (audits) during such measurements.

6 Concluding remarks

The EN 12354 series of standards on calculation methods facilitate the management of building acoustic issues during the building process. They may be used by a designer (e.g. an acoustician) to estimate the performance of buildings (e.g. sound insulation between rooms) from the performance of elements (e.g. floors and walls).

When measurement results from finalized buildings are used to prove the fulfillment of formal requirements (as stated by the building authorities or the commissioner), the calculations (made in an early phase of a project) must be on the safe side to minimize the risk of failure. However, in order to enable lean designs of the building constructions and choice of the most appropriate products on the market, the safety margins must not be exaggerated. Hence, it is important to determine them as accurately as possible.

The thesis presents comparisons, which have been used to estimate the combined uncertainty of the standardized methods and to derive safety margins to be observed during design work (i.e. to be added to calculated values). The combined uncertainty is estimated from the differences between field measurements of the performance of buildings with heavy concrete floors (made according to international standards) and the corresponding theoretical estimations in each case (according to calculation methods in the EN 12354).

The uncertainties of building element input data contribute to the combined uncertainty and a procedure that estimates their magnitude is described. Some problems are outlined in respect of the approximation of the calculation models to the real building constructions, effects of poor workmanship and uncertainty of the field measurement methods. Some results specifically address the uncertainty of the field measurement methods. Uncertainties may also pertain to unclear definitions of requirements (by the commissioner) and poor building construction documentation by the entrepreneur. A handbook has been written (briefly outlined in this thesis), which supports a structured way of describing requirements and establishing relevant documentation. This includes the use of the EN 12354 standards.

The process of evaluating the uncertainty, e.g. of new building elements, building techniques and measurement methods must be continuous and undertaken on each local building market. The thesis suggests future research on some issues that could help to reduce the safety margins and optimize the building constructions.

7 References

References underlined refer to papers published by the author in peer-reviewed journals (or submitted for publication in such journals). Where a peer-reviewed paper has been written together with another author, the degree of participation in the work has been indicated.

[1] Building acoustics - Estimation of acoustic performance of buildings from the performance of elements – Part 1: Airborne sound insulation between rooms.

[2] Building acoustics - Estimation of acoustic performance of buildings from the performance of elements – Part 1: Impact sound insulation between rooms.

[3] Building acoustics - Estimation of acoustic performance of buildings from the performance of elements – Part 3: Airborne sound insulation against outdoor sound

[4] Building acoustics - Estimation of acoustic performance of buildings from the performance of elements – Part 4: Transmission of indoor sound to the outside

[5] Building acoustics - Estimation of acoustic performance of building from the performance of elements - Part 5: Sounds levels due to service equipment. *The first section* treats models for airborne sound through ducts etc. *The second section* treats models for the structureborne sound through the equipment and the building structure.

[6] Building acoustics - Estimation of acoustic performance of buildings from the performance of elements – Part 6: Sound absorption in enclosed spaces

[7] European developments in prediction models for building acoustics. Gerretsen, E. TNO institute of applied physics, Delft, The Netherlands. Acta Acustica Vol 2, 1994, p 205-214.

[8] Building products - Treatment of acoustics in product technical specifications. CEN TC 126/WG 5 proposal prCEN/TR 15226:2005 (E). Brussels, 2005.

[9] On the uncertainty of single-number quantities for rating airborne sound insulation. Wittstock, V. Acta Acustica united with Acustica, Vol 93 (2007) p 375-386.

[10] Uncertainties in building acoustics. Wittstock, V. Proceedings of Forum Acusticum, Budapest 2005.

[11] Laboratory measurement of sound insulation in the frequency range 50 Hz to 160 Hz – A Nordic intercomparison. Olesen, H.S. Delta Akustik & Vibration. Nordtest report NT Tech 489 (2002).

[12] Unsicherheiten in der Bauakustik. Wittstock V. PTB-Mitteilungen 117 (2007), Heft 1

[13] Intercomparison of Laboratory Measurements of Airborne Sound Insulation of Walls. Pompoli R, Fairley R. University of Ferrara. http://web.unife.it/progetti/inter_lab/index.html, subpage color1.gif.

[14] ISO/WD 140-2 Acoustics — Measurement of sound insulation in buildings and of building elements — Part 2: Determination and application of uncertainties. ISO TC 43/SC 2/WG 18/ AHG 140-2. Secretariat: Danish Standards (DS).

[15] Treatment of Measurement Uncertainty in International and European Standards on Acoustics. BRINKMANN, K. ISO/TC 43 chairman, HIGGINSON R. CEN/TC 211 chairman, JACQUES J. INRS, NIELSEN L. Danish Standards Association (secretariat for the ISO 140-2). Plenary lecture, proceedings of Managing uncertainties in noise measurements and predictions. Symposium Le Mans, 26/29 june 2005. Order from http://www.bruit.fr/uncertainty/proceedings_eng.pdf

[16] ISO/IEC Guide 98-3:2008 Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)

[17] On the uncertainty of single-number quantities for rating airborne sound insulation. Wittstock, V. Acta Acustica united with Acustica, Vol 93 (2007) p 375-386.

[18] Measurement of the acoustical properties of buildings -- Additional guidelines. Olesen, H. Nordtest report NT tec 203 / TR 203. www.nordicinnovation.net.

[19] SS 25267 Acoustics – Sound classification of spaces in buildings – Dwellings. Ed 3 2004, amended 2009.

[20] SS 25268 Acoustics – Sound classification of spaces in buildings – Institutional premises, rooms for education, preschools and leisure-time centres, rooms for office work and hotels.

[21] BBR. Boverkets byggregler, BBR (BFS 1993:57 med ändringar t.o.m. 2008:6). Boverket building codes (of the National Board of Housing Building and Planning), available in English at www.boverket.se.

The codes give general requirements on the exposure to noise in dwellings and premises. BBR recommends sound class C of SS 25267 and SS 25268, c.f. ref 1 and 2.

[22] Sound insulation between dwellings - Classification schemes and building regulations in Europe. Rasmussen, B. Proceedings of Inter-noise 2004, Prague.

[23], Evaluation of sound insulation in the field. Hagberg K. G. Lund University of

Technology 2005. Rapport TVBA, ISSN 0281-8477

[24] Psychoacoustical Characteristics of impact Ball Sounds on Concrete Floors. Pyoung J.L, Kim J.H, Jin Y J. Acta Acustica Vol 95 2009, p707-717.

[25] Pedersen D.B. Delta Akustik & Vibration. Nordic basis of calculation of sound insulation in buildings. Report Nordtest project 1346-97. Aarhus 1999. Nordtest tech report NT Tech 425 (paper copies may be ordered from www.nordicinnovation.net).

[26] Calculation of acoustic data for concrete elements. Pedersen, D.B. Delta Akustik & Vibration client report K870149, Århus May 2001. This client report is made available (with permission) at http://www.simmons.se/redigerbart/BAC-223_Acoustic-data-concrete-elements_BASTIAN_DeltaAkustikVibration-DBP-WSP-BVI.PDF. The element data are tabulated in the handbook "Bygga med Prefab", available for download at www.byggamedprefab.se (text in Swedish, site offers English interface).

[27] The BASTIAN software is a registered trademark by Datakustik GmbH, Munich, www.datakustik.de The Nordic BASTIAN databases, www.bastian.nu, are managed by the author in cooperation with Dan Brösted Pedersen (DB Akustik, Århus) and since 2008 also by Sintef Byggforsk (Oslo/Trondheim).

[28] Sokrates. Warnock, Alf. Software available (free) at http://www.alfwarnock.info/sound/socindex.html

[29] Så byggdes husen (*Constructions of old houses*). L. Reppen et al. Report T1:1984, 5th edition. Formas publishers, Stockholm 2002. ISBN 91-540-5888-0. www.formas.se. *In Swedish.*

[30] SBUF 11254 Byggakustisk kunskapsöversikt - konstruktionsdatabas och praktiska erfarenheter. Rapport: Ljudisolering i bostadshus byggda 1880-2000 : praktiska erfarenheter och indata för beräkningar. Simmons, Christian (författare). Göteborg : Sveriges byggindustrier, 2004.Svenska 131 s. Serie: Rapport / FoU-Väst, 1402-7410 ; 0405. In Swedish. A summary is presented in ref.31.

[31] Reliable building element sound insulation data for EN 12354 calculations facilitates analysis of Swedish dwelling houses. Simmons C. Proceedings of inter-noise, Prague 2004.

[32] INSUL version 5.3. Marshall Day Acoustics New Zealand www.insul.co.nz

[33] Ljudisolering i bostadshus med stålstomme. Andersson, Johan. Stålbyggnadsinstitutet, Stockholm 1994 (In Swedish, with summary in English). ISBN/ISSN: 9171270027

[34] C. Johansson: Field measurements of 170 nominally identical timber floors: a statistical analysis. Proceedings of Inter-Noise 2000

[35] Sound Reduction in Buildings: models and means to realize required acoustic quality. Gerretsen E. From slides presented at a keynote presentation at the Nordic conference BNAM 2008, Reykjavik, Iceland.

[36] Structure-borne sound transmission through plate junctions and estimates of SEA coupling loss factors using the finite element method. Author(s) SIMMONS C. Journal of sound and vibration ISSN 0022-460X. 1991, vol. 144, no2, pp. 215-227.

[37] Robust Estimation of Coupling Loss Factors from Finite Element Analysis. Mace B.R. and Thite A.N. Proceedings of inter-noise, Prague 2004.

[38] Sources of uncertainties in vibro-acoustic simulations. Coyette, J-P. Proceedings of Managing uncertainties in noise measurements and predictions. C.f. reference 15.

[39] The importance of in-plane waves in sound transmission through buildings. Applied Acoustics, Volume 37, Issue 2, 1992, Pages 85-109. Craik, R. J. M. and Thancanamootoo, A.

[40] Measurement of SEA Coupling Loss Factors using Point Mobilities, by C. Cacciolati and J. L. Guyader. Phil. Trans. of Royal Society of London. A (1994) Vol 346, p 465.

[41] Application of practical facade sound insulation requirements in Sweden. Simmons C. Proceedings of Euronoise, Tampere 2006

[42] Fönster med hög ljudisolering mot trafikbuller : ett samverkansprojekt inom svensk fönsterindustri. Simmons, Christian (författare). ISBN 91-7848-732-3. Borås : Sveriges provnings- och forskningsinstitut (SP), 1998. Svenska 61, [48] s. Serie: SP rapport, 0284-5172 ; 1998:26.

[43] Ljudklassning av fönster. Jonasson, H G. Rapport R125:1985. Statens råd för byggnadsforskning (Byggforskningsrådet). ISBN 91-540-4474-X

[44] Håndbok 47 – Isolering mot utendørs støy. Beregningsmetode og datasamling. Hveem S and Homb A. Norges byggforskningsinstitutt 1999. ISSN 0048-0517. ISBN 82-536-0660-5.

[45] Reduction of external noise by building facades: tolerance of standard EN 12354-3. Saarinen A. Applied Acoustics, Volume 63, Number 5, May 2002 , pp. 529-545(17). Elsevier.ISSN: 0003-682x.

[46] Errors when using façade measurements of incident aircraft noise. Bradley, J.S.; Chu, W.T. Proceedings of inter-noise 2002, Dearborn USA. Report NRCC-45384, National Research Council, Ottawa, Canada.

[47] Prediction model for sound transmission from machinery in buildings: Feasible approaches and problems to be solved. Noise-Con Proc. Volume 204, Issue 1, pp. 413-419. Gerretsen, E. Proceedings of inter-noise 2000, Nice, France.

[48] Prediction models for building performance – European need and world wide use. Gerretsen, E. Proceedings of Euronoise/Acoustics 08, Paris 2008. www.acoustics08-paris.org.

[49] Comparison of predicted and measured structure-borne sound of an industrial washing machine on a heavy concrete floor. Schevenels P, de Geetere L, Ingelaere B. Proceedings of inter-noise 2009, Ottawa, Canada.

[50] Determination of structure-borne sound source strength for building service equipment – a pilot study with inter-laboratory comparisons and a proposal for a Nordtest method. Larsson K, Simmons C. Available as Nordtest report NT Tec 616 at www.nordicinnovation.net.

[51] NT ACOU 117 - Determination in the field of structure-borne sound source strength of building service equipment. Available at www.nordicinnovation.net.

[52] Measurements of structure-borne sound from building service equipment by a substitution method – inter-laboratory comparisons. LARSSON K, SIMMONS C. *Manuscript submitted to Noise Control Engineering Journal in September 2009. The authors have cooperated during all parts of the work and written the paper together, except for the field tour that the author conducted alone.*

[53] Structure-borne sound power input in low-mobile concrete plates. Kihlman T, Simmons C. Department of Applied Acoustics, Chalmers University of Technology, Gothenburg,1988. Report F0283. The report is available in two PDF-files, at http://www.simmons.se/redigerbart/SBS-Lws-input_012.PDF.zip and http://www.simmons.se/redigerbart/SBS-Lws-input_345.PDF.zip

[54] How to improve the accuracy of the absorption measurement in the reverberation chamber? Vercammen, M.L.S. Peutz bv, Mook, The Netherlands. Proceedings of DAGA 2009.

[55] Minimum area covered by a sound absorber estimated from its ISO 11654 classification and required reverberation time. Simmons, C. Proceedings of Euronoise 2009, Edinburgh.

[56] Reproducibility of measurements with ISO 140 and calculations with EN 12354. ISSN: 0283-7234. C Simmons, Nordic Innovation Centre, Oslo 2005. NT TECH 603. www.nordicinnovation.net/nordtest.cfm

[57] Uncertainty of measured and calculated sound insulation in buildings: Results of a Round Robin Test. Author(s) SIMMONS C. Noise control engineering journal ISSN 0736-2501. 2007, vol. 55, no 1. *This paper comprises results both from a round robin on the uncertainty of field methods for airborne and impact sound insulation and comparisons of field results to calculation results.*

[58] Unsicherheiten in der Bauakustik. Wittstock, V. PTB-Mitteilungen 117 (2007), Heft 1. www.ptb.de

[59] The Probability Density Functions and the Uncertainty of the EN12354 Prediction Method. Mahn Jeffrey and Pearse John. Proceedings of inter-noise 2008.

[60] Uncertainty of measured and calculated sound insulation in buildings. Simmons, C. Conference, Le Mans , FRANCE (06/2005). C.f. reference 15.

[61] SOUND INSULATION IN AUSTRIAN MULTIFAMILY HOUSES. LANG J. Proceedings of inter-noise 2000, Nice. Original source and Figure from Lang, J: Ergebnisse des Vergleichs von Messwerten des Schallschutzes in Gebäuden mit Rechenwerten nach EN12354. wksb Heft 47/2001.

[62] The prediction of airborne sound transmission between two rooms using first-order flanking paths. Galbrun, L. Applied Acoustics, Volume 69, Issue 12, December 2008, Pages 1332-1342.

[63] Innovative building systems to improve the acoustical quality in lightweight masonry constructions: Application of resilient junctions at junctions – PART 2: Study cases modelled according to the standard 12354-1 (2000). Crispin C., Ingelaere B. and Wuyts D. Proceedings of Euronoise 2008/Acoustics 08, Paris 2008.

[64] Vibration transmission indices at junctions with cavity walls. Martin H.J., Smits J.P., Niggebrugge J.W., Gerretsen E, van Luxemburg L.C.J.. Proceedings of internoise 2004.

[65] Direct and flanking sound transmission of solid gypsum walls – practical experience and numerical prediction. Ruff, A. and Fischer H.-M. Proceedings of Euronoise 2008/Acoustics 08, Paris 2008.

[66] Uncertainty of predictions in building acoustics. Wittstock, V. PTB, Scientific news from Division 1. w

[67] Bostäder och nya ljudkrav. Rapport till Byggkostnadsdelegationen (byggkostnadsforum). Boverket september 2007. ISBN: 978-91-85751-43-3. In Swedish. A summary is made in ref. 68.

[68] Consequences of new building regulations for modern apartment buildings in Sweden. Hagberg K, Simmons C. Proceedings of inter-noise 2006, Honolulu.

[69] Measurements of sound pressure levels at low frequencies in rooms : comparison of available methods and standards with respect to microphone positions : proposal for new procedures. Simmons, Christian (författare). ISBN 91-7848-685-8. Borås : Swedish National Testing and Research Institute, 1997. In English. Serie: SP report ; 1997:27. Available as NT Tec 385, http://www.nordicinnovation.net/nordtestfiler/nt385.pdf

[70] Socialstyrelsens allmänna råd "Buller inomhus och höga ljudnivåer" 1996:7 (M). Superseeded 2005 by the new recommendation ”Buller inomhus. SOSFS 2005:6(M). www.socialstyrelsen.se

[71] Vägledning för mätning av ljudnivå i rum vid låga frekvenser : fältprovning. SP Info 1996:17. Simmons, Christian (författare). Sveriges provning- och forskningsinstitut (medarbetare). Borås : Sveriges provnings- och forskningsinstitut, 1996. Svenska. Serie: SP-INFO, 99-0400185-5. (Mätanvisning för kontroll enligt Socialstyrelsens allmänna råd "Buller inomhus och höga ljudnivåer" 1996:7 (M).

[72] Measurement of Sound Pressure Levels at Low Frequencies in Rooms. Comparison of Available Methods and Standards with Respect to Microphone Positions. SIMMONS C. Acta Acustica united with Acustica, Vol 85, No 1, Jan 1999 , pp. 88-100(13). S. Hirzel Verlag.

[73] Comparison of methods and standards for the measurement of sound pressure levels at low frequencies in rooms. Simmons, C. 8th Int. Conf. on Low Frequency Noise. Hotell 11 Göteborg april 1997.

[74] ON MEASURING LOW-FREQUENCY NOISE INDOORS. Pedersen S, Møller H, Persson Waye K. Proceedings of B-NAM 2008, Reykjavik.

[75] Spatial sampling of sound pressure in rooms using manual scanning paths. C Hopkins, Acoustics Research Unit, School of Architecture, University of Liverpool. Proceedings of Euronoise 2009, Edinburgh.

[76] Statistical characteristics of some standard reverberant sound field measurements. Bodlund, K. J. of Sound and Vibration, Vol 45(4), p 539-557, 1976.

[77] On the uncertainty of sound pressure levels determined by third-octave band analyzers in a hemianechoic room. Bethke, C and Wittstock V. Proc. of Forum Acusticum 2005, Budapest.

[78] C Simmons, Measurement of Noise from Radiator Valves in the laboratory – A Proposal for a New Nordtest Method, SP Report 1996:31. The method is adopted by NORDTEST as NT ACOU 101.

[79] Sound absorption and suspended ceilings. Larsson K. Proceedings of B-NAM 2006, Gothenburg.

[80] Verification of sound absorption measurements. Simmons C. Proceedings of Euronoise 2006, Tampere.

[81] Lydforhold i undervisnings- og daginstitutionsbyggeri. Ajourføring af kravniveauet. Februar 2003. Erhvervs- og Boligstyrelsen. Based on a report by Dan Hoffmeyer, DELTA Acoustics & Vibration.

[82] http://www.sis.se/PDF/2009-04-29_FAQ_SS_25267_och_SS_25268.pdf

[83] VDI 4100:1994, “Schallschutz von Wohnungen - Kriterium für Planung und Beurteilung“

[84] APPROVED DOCUMENT E. Resistance to the passage of sound. Office of the Deputy Prime Minister (England). The Building Regulations 2000. The Building (Approved Inspectors etc) Regulations 2000. Annex E: Design details approved by Robust Details Ltd (www.robustdetails.com)

[85] Bullerskydd i bostäder och lokaler (in Swedish). Hagberg, K.G, Simmons, C. Boverket (National Board of Housing Building and Planning), Karlskrona 2008 (Note: an English summary is given in the next reference). Printed version: ISBN 978-91-86045-40-1. PDF-version at www.boverket.se: ISBN 978-91-86045-41-8. ISSN: 1400-1012.

[86] A handbook on the management of acoustic issues during the building process. HAGBERG K, SIMMONS C**.** Submitted to Journal of Building Acoustics in October 2009. *The authors have cooperated during all parts of the work and written the paper together*.

Papers

1. Structure-borne sound transmission through plate junctions and estimates of SEA coupling loss factors using the finite element method. Author(s) SIMMONS C. Journal of sound and vibration ISSN 0022-460X. 1991, vol. 144, no2, pp. 215-227.
2. Measurements of structure-borne sound from building service equipment by a substitution method – inter-laboratory comparisons. Larsson K, Simmons C. *Manuscript submitted to Noise Control Engineering Journal, September 2009*.
3. Uncertainty of measured and calculated sound insulation in buildings: Results of a Round Robin Test. Author(s) SIMMONS Christian. Noise control engineering journal ISSN 0736-2501. 2007, vol. 55, no 1.
4. Measurement of Sound Pressure Levels at Low Frequencies in Rooms. Comparison of Available Methods and Standards with Respect to Microphone Positions. Simmons, C. Acta Acustica united with Acustica, Vol 85, No 1, Jan 1999 , pp. 88-100(13). S. Hirzel Verlag.
5. A handbook on the management of acoustic issues during the building process. *Manuscript submitted to Journal of Building Acoustics, October 2009.*
6. Reliable building element sound insulation data for EN 12354 calculations facilitates analysis of Swedish dwelling houses. Simmons C. Proceedings of Inter-noise, Prague 2004.
7. Verification of sound absorption measurements. Simmons C. Proceedings of Euronoise 2006, Tampere.
8. Minimum area covered by a sound absorber estimated from its ISO 11654 classification and required reverberation time. Simmons, C. Proceedings of Euronoise 2009, Edinburgh.

Paper I

Journal of Sound and Vibration (1991) **144**(2), 215-227

STRUCTURE-BORNE SOUND TRANSMISSION THROUGH PLATE JUNCTIONS AND ESTIMATES OF SEA COUPLING LOSS FACTORS USING THE FINITE ELEMENT METHOD

C. SIMMONS

Department of Applied Acoustics, Chalmers University of Technology, S-412 96 Gothenburg, Sweden

(*Received* 25 *November* 1988, *and in revised form* 16 *October* 1989)

The finite element method (FEM) is used to calculate the vibrational energies of plates forming L- and H-structures at discrete frequencies between 10 and 2000 Hz, where one plate is excited by a point force and the power is transmitted through the junction to the other plates. The energies can be used to characterize the transmission of structure-borne sound through that junction. The results agree very well with the results from measurements and classical theoretical methods. It is observed that the displacements predicted by FEM at individual positions and frequencies are not reliable, because both the discretized model and the discrepancies between the real and the modelled plate properties and boundary conditions shift the mode shapes and the eigenfrequencies. The average energy of a plate, derived from the squared and spatially averaged displacements in a frequency band, is easier to interpret and generally more accurate than the predicted displacements at individual positions and frequencies. The coupling loss factor of a junction can be derived from such averaged energies of the plates that form the junction. The coupling loss factor characterizes the specific type of junction that is analyzed and it can be applied in statistical energy analyses (SEA) of structures with the same type of junction.

1. INTRODUCTION

In this paper an analysis is presented of the transmission of structure-borne sound (or any vibrational power flow) through junctions between plates, where the finite element method (FEM) has been applied. Prediction tools are needed in several fields of acoustics for the analysis of complicated types of junction; e.g., in flanking transmission problems in buildings, or in vibration problems such as power flow between plates in vehicles.

Several analytical methods have been developed in this field, based either on modal analysis, or on statistical energy analysis. A "junction" is described by the number of plates and the shape; e.g., L-, T- and +- shapes. It is also described by the way in which the plates are connected; e.g., at points, along lines or by a beam. The modal analyses have been applied successfully to structures of rectangular isotropic plates which are connected rigidly at right angles to form a junction, with a few types of constraint at the other edges of the structure [1-4]. Statistical energy analysis (SEA) is widely used to give an estimate of the average power flow within frequency bands in cases where the vibration fields can be assumed to be diffuse [5-10]. The coupling loss factors η_{jk} used in SEA are often derived from averaged transmission factors of plane waves that are transmitted through an infinite junction between semi-infinite plates. However, many problems of practical importance cannot be analyzed with these analytical methods.

The main purpose of a long-term study at the department is to develop a method based on FEM that can serve as a general tool in the analysis and the characterization of an arbitrary type of junction. The reason for choosing FEM is that the method is very general.

0022-460X/91/020215+13 $03.00/0

It is in principle possible to characterize almost any type of junction; e.g., discontinuous, curved, point connected and stiffened junctions between any structural members. Although numerical methods have been applied to entire structures or to coupled beams (mainly in the low-frequency range), no references have been found to any applications of FEM similar to that presented here. It is clear that even if small structures (or fractions of a large structure) can be analyzed by using FEM directly, it is often unfeasible to apply FEM to entire structures because the number of modes that would have to be computed are prohibitive.

One application of FEM that could be of practical interest is suggested in this paper. Complex structures that would be difficult to analyze with either FEM or SEA could possibly be analyzed with FEM and SEA combined. These structures could be analyzed in two steps, where FEM is applied first to give the η_{jk} of the junctions of the structure, then these η_{jk} are used in a second step in an SEA calculation to give the average energy distribution between all the plates of the entire structure. The estimates of the average coupling loss factors η_{jk} of each type of junction in the structure can be derived from spatially and frequency band averaged displacements of the plates that have been calculated with FEM. In this context, SEA itself is in no way involved in the development of the FEM method for calculating the spatially and frequency band averaged displacements. This proposed combination of FEM and SEA for a complex structure is only one possible important application of the FEM results.

It was necessary to verify that FEM could be applied to simple structures which could be analyzed with other methods before proceeding to complicated junctions. Therefore, this study deals with structures such as simple rectangular isotropic plates and different types of junction between such plates. Measurements, analytical methods and SEA have been used to verify the FEM results in these cases.

The finite element method program ABAQUS and a VAX 2000 Workstation computer are used in this study. Any similar type of computer makes the calculations very inexpensive but also limits the size of the structures that can be analyzed. However, the applicability of the method suggested in this paper may increase in the near future because of current hardware and software improvements: it is therefore interesting to undertake preparatory studies and gain experience of this particular application of FEM, even if the computation times presently prohibit many applications of interest.

Nevertheless, there are several reasons for avoiding deterministic and detailed full-scale acoustical analyses of complex structures by FEM. The output of a FEM calculation is the displacements of a structure at all positions (the nodes) and at fixed frequencies. For two reasons, this information is not exact, and should not be used directly. Firstly, eigenfrequency errors occur at higher frequencies even in a "correct" finite element model as a result of the discretization (see Figure 1). Secondly, various discrepancies between the real and the assumed material properties, boundary conditions and shapes of the structures are almost inevitable when a complex structure is modelled. The calculated mode shapes and the eigenfrequencies of the FE model may be shifted relative to the real mode shapes and eigenfrequencies; therefore the displacements at discrete positions and frequencies may be erroneous. However, this shift of the mode shapes and eigenfrequencies in FEM can be considered as random. If the calculated displacements are integrated over each plate and simultaneously over a frequency band, it appears that these spatial and frequency band averages of the displacements are sufficiently accurate to give an estimate of the vibrational energy of a plate. The ratios of the vibrational energy between the plates that form a junction is used to define a coupling loss factor that describes the transmission through the junction.

An important reason to why FEM is used to calculate a statistical parameter such as the coupling loss factor is that it may prove as safe to apply SEA to complex structures

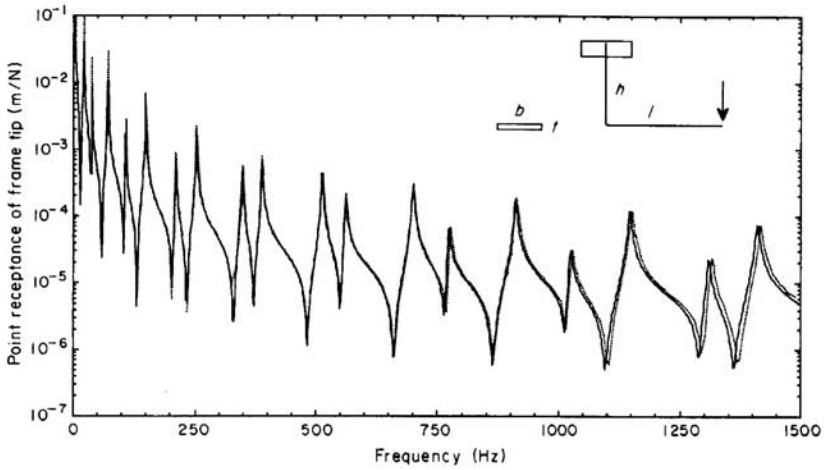


Figure 1. Point receptance of the free end of a steel frame, with the other end clamped. ——, Predicted with an exact frame analysis [17]; · · · ·, predicted with FEM. Dimensions and material properties of the structure: $b = 0{\cdot}012$ m, $t = 0{\cdot}002$ m, $h = 0{\cdot}500$ m, $l = 0{\cdot}600$ m, Young's modulus 210×10^9, density 7800 kg/m^3, damping loss factor 0·005.

as to apply FEM directly. Exact details about a structure are rarely known early in a design process when decisions are being made about the structure. This problem is of course inherent in all prediction methods, but it is emphasized in FEM because the model must be described in every detail and the results are valid for that model only. SEA does not reveal such detailed information about the vibrations as a direct output from FEM *appears to do.* Both the FEM- and the SEA-predicted vibration levels may be quite different from the real values at individual positions and frequencies. When SEA is used, it may be easier to establish a model of the structure, assess the relative importance of uncertainty in the input data and interpret the results.

2. THEORY

2.1. APPLICATION OF THE FINITE ELEMENT METHOD

In this section the development of a finite element model and some aspects of the difficulties encountered are discussed. The finite element method is described in reference [11] and the ABAQUS finite element program used in this work is described in reference [12]. All input data are structured by a preprocessor within this program.

Rectangular, isotropic and homogeneous plates with various boundary conditions are modelled as assemblies of thin shell elements (ABAQUS eight-node S8R5) that include shear deformation (Timoshenko shell theory). The elements are connected at the nodes. Static parabolic shape functions are used for the displacements and the mass and stiffness matrices of the elements. Composite materials and stiffened plates can be modelled. The damping of each material is given as the fractions ζ of the critical modal damping of each mode in a range of modes. Each ζ is weighted with the participation of the material in the mode which gives the total damping of each mode [12].

A systematic variation of the element mesh showed that the mode shapes of the FE model are acceptable for the purpose of this study if the element mesh is dense enough to contain at least three parabolic elements per wavelength of the bending waves, or six linear elements with lumped masses. The dimensions of each element must be greater than about five times the thickness t of the plate. This implies that the upper frequency limit is given by the condition that the bending wavelength $\lambda_B > 15t$.

The response of the plates to a harmonic point force excitation at a given node is calculated directly in the frequency domain by a modal superposition procedure (ABAQUS Steady State Dynamics) which allows many frequency points to be calculated efficiently. All modes with the eigenfrequencies within the frequency range of interest (10 Hz–2 kHz) were used in the superposition procedure. In the case of large structure models, however, it is possible to use a shifting technique in order to reduce the computation time. The eigenfrequencies within a frequency band can be extracted and only the resonant modes in that frequency band will then be used in the superposition procedure. The loads, the material properties and the boundary conditions can easily be changed for each set of frequency points.

As all the six degrees of freedom are considered at every node in a FEM analysis, one may expect that all thin plate wave types were to be included in the analysis. Numerical errors may occur at nodes where impedances of significantly different magnitudes are added; e.g., at junctions between plates with different thicknesses. It is difficult to prove that the conversions between in-plate waves and bending waves at a junction are calculated correctly with FEM. An H-structure formed by five thick Perspex plates (0·015 m) was used to study whether the out-of-plane displacements would be affected by translational constraints on the junctions of the H-structure (see section 3.1.2).

2.2. ACCURACY OF THE METHOD: COMPARISONS BETWEEN THEORY AND MEASUREMENTS

A few cases of simply supported and free–free coupled rectangular plates were measured and analyzed with FEM and other theoretical methods in the frequency range 10 Hz to 2 kHz [10, pp. 282–297]. The simply supported plates were compared with respect to the eigenfrequencies, the mode shapes and the point receptances.

The displacements of the coupled plates, measured in narrow bands or FEM-calculated at discrete frequencies ω, were compared with each other and with the average energy content of each plate calculated by using SEA. In order to make these quantities comparable, the kinetic energy $\langle E_j \rangle$ on a plate j was derived from the measured or the calculated displacements p_n at N evenly distributed points,

$$\sum_{n=1}^{N} m''_{nj}\omega^2 p_{nj}^2 S_{nj} = \langle E_j \rangle, \tag{1}$$

where ω is the angular frequency, S_{nj} is the fraction of the area of the plate that is lumped to the point n and m''_{nj} is the mass density of this fractional area. More than four points per wavelength (in all directions) were used in the mesh in order to suppress the error in this estimate of $\langle E_j \rangle$ to an acceptable level. The energy ratio between a plate k and an excited plate j is

$$\langle E_k \rangle / \langle E_j \rangle. \tag{2}$$

The $\langle E \rangle$ represents the total energy of a plate—which is the SEA quantity—if it is averaged within frequency bands $\langle E_{\Delta\omega} \rangle$ that are wide enough to contain a few resonant modes.

The energy ratio was also calculated theoretically in one-third octave bands by using SEA. In this SEA calculation, the coupling loss factors were derived from the theoretical average transmission factor τ_{jk} which describes the transmission efficiency of a diffuse field of bending waves that are incident upon the junction. This τ_{jk} can be derived from a wave analysis of semi-infinite plates, connected rigidly at right angles along an infinite junction [9, 10]. The τ_{jk} gives an estimate of the average energy ratio which is, in the case

of two plates [6],

$$\tau_{jk} = [\pi\omega\eta_k\langle E_{k,\Delta\omega}\rangle]/[l_{jk}2c_{Bj}\langle E_{j,\Delta\omega}\rangle/S_j], \tag{3}$$

and τ_{jk} is related to the mean coupling loss factor η_{jk},

$$\eta_{jk} = [2l_{jk}c_{Bj}\tau_{jk}]/[\pi\omega S_j], \tag{4}$$

where η_k is the loss factor of plate k, l_{jk} is the length of the junction, c_{Bj} is the bending wave velocity and S_j is the area of the excited plate j [19]. The results are discussed in section 3.

2.3. SEA AND THE COUPLING LOSS FACTORS

A description of statistical energy analysis (SEA) has been given by Lyon [13]. A structure is idealized into an assemblage of individual subsystems; the plates are the subsystems in this study. The subsystems are coupled through the common boundaries: i.e., through the junctions. The energy dissipated by a subsystem is characterized by the dissipative loss factor and that transferred to the connected subsystems by the coupling loss factors. The spatially averaged vibrational energy of each plate (or on any subsystem) in a frequency band $\langle E_{j,\Delta\omega}\rangle$ that is wide enough to contain several resonant modes can be obtained from an energy balance equation,

$$\begin{pmatrix} \eta_{11} & -\eta_{21} & -\eta_{31} & \cdots & -\eta_{j1} \\ -\eta_{12} & \eta_{22} & -\eta_{32} & \cdots & -\eta_{j2} \\ \vdots & & & & \vdots \\ -\eta_{1j} & -\eta_{2j} & -\eta_{3j} & \cdots & \eta_{jj} \end{pmatrix} \begin{pmatrix} \langle E_{1,\Delta\omega}\rangle \\ \langle E_{2,\Delta\omega}\rangle \\ \vdots \\ \langle E_{j,\Delta\omega}\rangle \end{pmatrix} = \begin{pmatrix} P_1/\omega \\ P_2/\omega \\ \vdots \\ P_j/\omega \end{pmatrix}, \tag{5a}$$

where $[P_1 \cdots P_j]$ are the power inputs to the subsystems and η_{ii} represents all the losses of the subsystem i in the frequency band $\Delta\omega$,

$$\eta_{ii} = \eta_i + \sum_{k=1, k\neq i}^{j} \eta_{ik}. \tag{5b}$$

Two properties of the η_{jk} can be concluded from the derivation of τ_{jk} [9] that are important in the discussion of how to apply FEM in order to derive the η_{jk} of a junction.

Firstly, the junction between the plates defines the mechanical coupling of the plates and thus affects the average power flow in a frequency band. The power flow in an individual structure can be related to a η_{jk}, but this η_{jk} is only valid for that structure.

Secondly, the dimensions of the plates and the constraints at the other edges do not have much influence on the average power flow as long as the plates are large enough to have a number of resonant modes within each frequency band, but they determine the frequencies at which the modes of the plates are strongly coupled: i.e., where the main transmission occurs.

This means that a representative average of the η_{jk} can be derived from an ensemble of structures with the plates coupled in the same way; the average of all η_{jk}s characterizes the junction. The average η_{jk} can be applied in SEA in each case where the plates are coupled in the same way.

It is therefore suggested that the FE models should be varied with respect to the sizes, the shapes and the constraints at the edges of the plates (except the junction) in order to establish an ensemble of energy ratios that can be used to calculate the average η_{jk}. The plates of the FE model must be large enough to contain several resonant modes within the frequency bands of interest. In section 3.2, the energy ratios of a Perspex structure calculated at closely spaced frequencies (including the global eigenfrequencies)

for various constraints at the edges of the structure and for various material properties are presented.

In the case of two plates coupled in any type of coupling path, the η_{jk} can be estimated from the frequency band averaged energy ratios as

$$\langle E_{k,\Delta\omega}\rangle/\langle E_{j,\Delta\omega}\rangle = \eta_{jk}/\{(n_j/n_k)\eta_{jk}+\eta_k\}, \tag{6a}$$

$$\eta_{jk} = (n_k/n_j)\eta_k/\{(n_k/n_j)(\langle E_{j,\Delta\omega}\rangle/\langle E_{k,\Delta\omega}\rangle)-1\}, \tag{6b}$$

where the ratio n_k/n_j is an estimate of the ratio of the modal densities of the plates j and k [14]. When the energy ratios obtained from an FEM analysis are applied to equations (6) to evaluate the η_{jk}, the dissipative losses η_k should preferably be much greater than the η_{jk}. This is because even small errors in the energy ratios influence the result strongly if the ratio of the modal densities n_k/n_j is close to unity [15].

If the junction consists of more than two plates, the coupling loss factors must be calculated through the fitting of the energies obtained from cases with several excitation positions on each plate to the coefficients in the matrix equation (5). As is discussed in references [20, 21, 14, 15], the accuracy of the results is very sensitive to small errors in the energies. When the energies are calculated by using FEM, one can utilize the fact that FEM makes it possible to set the damping of the plates to a range of values (to zero, e.g.) and that a range of excitations can be established very conveniently. This means that very many different energy estimates could be used in the matrix fitting procedure in order to improve the accuracy, this is often difficult to do when measurements are carried out on a physical model.

In some applications, the expected maximum vibration level on a plate is of interest rather than the mean level and it would be valuable to be able to predict not only the average η_{jk} but also a confidence interval of the η_{jk}. Generally, the variation within the ensemble of energy ratios (discussed above) is representative only for the structures that have been analyzed—the variation cannot be generalized to all structures. When the measurement objects or the FE models have approximately the same modal densities as the structure that is modelled, the uncertainty in the estimate of the η_{jk} could be assessed from the measured or the FEM-calculated ensemble of n energy ratios: e.g., as the variance of η_{jk},

$$\mathrm{Var}\,[\eta_{jk}] = \frac{1}{n-1}\left[\left(\sum_{i=1}^{n}\eta_{jk}^{i2}\right)-\bar{\eta}_{jk}^{2}\cdot n\right]. \tag{7}$$

3. RESULTS

3.1. ACCURACY OF THE METHOD: COMPARISONS BETWEEN THEORY AND MEASUREMENTS

3.1.1. *Preliminary studies*

It was necessary to check that the ABAQUS finite element method program produces valid results, especially since no published work was found on this particular use of FEM in the frequency range 10 Hz to 2 kHz. Several simple cases were examined by using FEM that could readily be compared with the results from measurements and theoretical methods.

Firstly, three plate problems were studied. (1) Eigenfrequencies of a square, simply supported steel plate (area 0·36 m^2, thickness 0·002 m) were compared with the theoretical eigenfrequencies [10]. (2) Very efficient absorption was added to the FE model of the

plate in a strip close to the supports, and the point mobility of this non-reverberant plate was compared with the point mobility of an infinite plate [10]. This technique of making an FE model non-reverberant—or semi-infinite—has not been reported before. It is a very useful technique in some cases. (3) A Perspex plate (area $0{\cdot}500 \times 1{\cdot}00\ \mathrm{m}^2$, thickness $0{\cdot}015$ m) was freely suspended, and the measured eigenfrequencies and the mode shapes were compared below 500 Hz. In all three cases the FEM results compared very well with the predicted and/or the measured values. The stiffness and the damping properties of the Perspex could be extracted from the measured transfer functions and be used in the FE model of the H-structure that is discussed below.

Secondly, in Figure 1 is shown a frame of two thin steel beams that was analyzed with FEM and with the computer program SFVIBAT that calculates the modes in frames of Timoshenko beams exactly [17]. The point receptance in the frequency range 10–1500 Hz was calculated. The agreement is very good.

Thirdly, the spatially averaged energy ratio of two coupled steel plates 1 and 2 forming an L-structure (see Figure 2) was measured and calculated by using FEM. The energies were also calculated in one-third octave bands by using SEA with the η_{jk} from equation (4). The structure was freely suspended because this boundary condition can be implemented exactly. The receiving plate 2 was damped by a free layer of visco-elastic material (in order to obtain $\eta_2 \gg \eta_{12}$—see section 2.3) and the modal damping factors for each plate were measured with the other plate kept constrained. The damping of each global mode was calculated according to section 2.1 by using the average of the modal damping factors of each plate, $\zeta_2 = 10^{-2}$ and $\zeta_1 = 5 \times 10^{-4}$, for simplicity. The loss factor η_2 used in the SEA calculation was taken as $\eta_2 = 2\zeta_2$. Plate 1 was point force excited at a free corner to ensure that many modes were excited. The measurement positions were the same as the nodes of the element mesh, which gives a random error in the energy estimates of the order of 3–5 dB at higher frequencies. The magnitudes of the transfer receptance from each position in the mesh were measured in order to normalize the response with the force in the frequency range 80–2000 Hz, squared and summed according to equation (1). Finally, the energy ratios between the plates were calculated (equation (2)). The energy ratio calculated by using FEM does not fit the measured ratio at all peaks, but the frequency band averages of the measured and the FEM-calculated values agree well and are close to the SEA-calculated values in Figure 2.

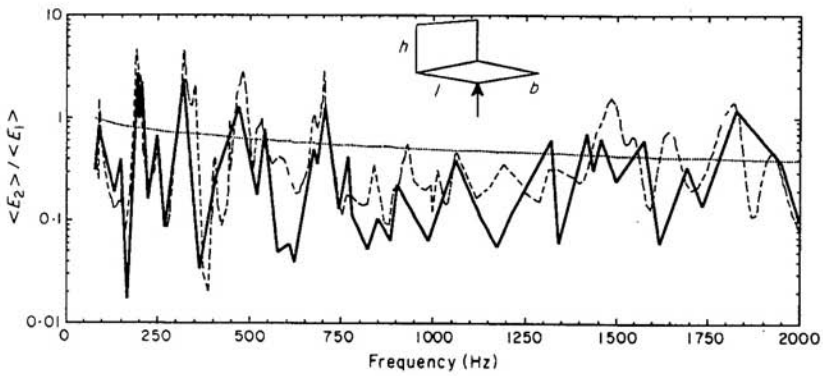


Figure 2. The energy ratio $\langle E_2 \rangle / \langle E_1 \rangle$ of a junction between two steel plates forming an L-structure, suspended in soft springs, excited at a corner. ——, Experimental values in narrow bands; - - -, discrete frequency values predicted by using FEM; · · · ·, one-third octave band values predicted by using SEA. Dimensions and material properties of the structure: $b = 0{\cdot}280$ m, $t = 0{\cdot}002$ m, $h = 0{\cdot}400$ m, $l = 0{\cdot}320$ m. The average of the modal damping factors of each plate are $\zeta_2 = 10^{-2}$ and $\zeta_1 = 5 \times 10^{-4}$.

These preliminary studies were presented and discussed in 1988 at the Nordic Acoustical Meeting in Tampere, Finland [18]. The results from the analyses of the frame and the L-structure show good agreement in general, but further questions were raised at the conference about the influence of the mesh density, the number of measurement points on the averaged energies (in equation (1)) and whether in-plane waves were included correctly in the FEM calculation in the case of thick plates.

3.1.2. *Studies of an H-structure formed by five Perspex plates*

The spatially averaged energy ratios of five Perspex plates forming an H-structure (see Figure 3) were measured and calculated by using SEA and FEM. The measurement procedure and the FEM calculation were analogous to those for the L-structure. The SEA calculation of the energies was made by a computer program [19] that derives the coupling loss factors in equations (5). The transmission factors between all coupled plates and all thin plate wave types were calculated and averaged over all angles of the incident

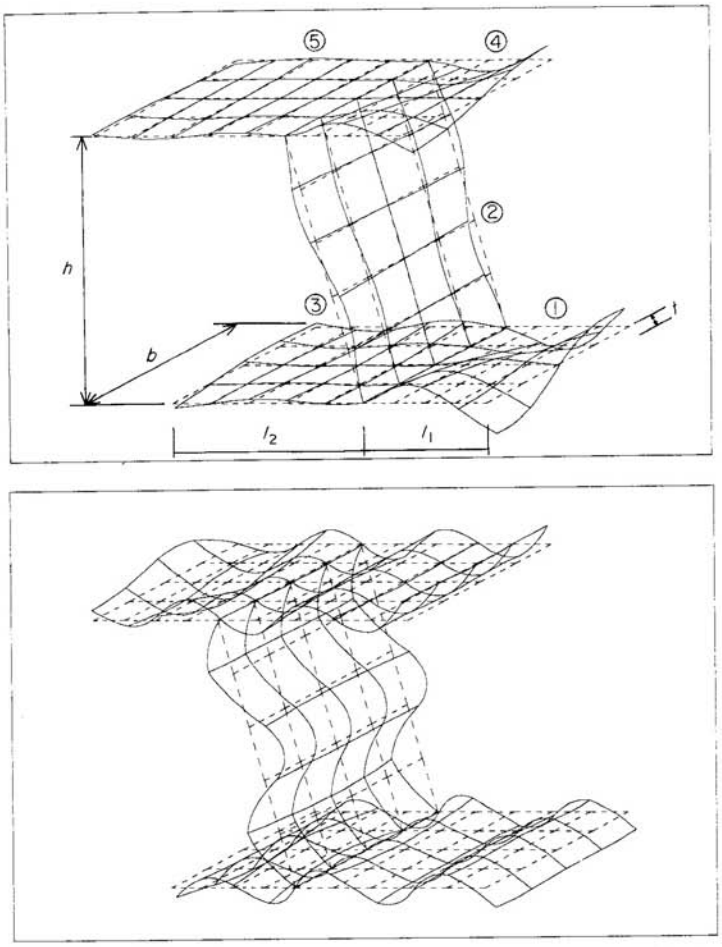


Figure 3. Five Perspex plates forming an H-structure, suspended in soft springs, excited at a corner. - - -, The element mesh; ——, illustrating two mode shapes; top, frequency 584 Hz; bottom, frequency 900 Hz. Dimensions and material properties of the structure: $b = 0{\cdot}300$ m, $t = 0{\cdot}015$ m, $h = 0{\cdot}415$ m, $l_1 = 0{\cdot}260$ m, $l_2 = 0{\cdot}400$ m, Young's modulus $4{\cdot}9 \times 10^9$, density 1180 kg/m^3.

waves giving the coupling loss factors, on the assumption that the wave fields on each plate were diffuse.

The dimensions of the H-structure and the element mesh, and also two modes of vibration, are shown in Figure 3.

The measured and the calculated energy ratios of plates 2 and 1 are shown in Figure 4(a) and those of the plates 5 and 1 in Figure 4(b). The Young's modulus ($4{\cdot}9 \times 10^9$) and an average of the modal dampings ($\zeta = 0{\cdot}03$) were fitted to the values obtained from the measurements on a free-free plate made of the same material (see section 3.1.1). The FEM-calculated vibrational energy is lower than the measured energy, but the curve is still close and both curves agree well on the average with the one-third octave band values calculated by using SEA.

The damping was then changed to $\zeta = 0{\cdot}03$ (10–350 Hz), $\zeta = 0{\cdot}02$ (350–500 Hz), $\zeta = 0{\cdot}015$ (500–800 Hz), $\zeta = 0{\cdot}01$ (800–1200 Hz) and $\zeta = 0{\cdot}0075$ (1200–2000 Hz). These values are closer to the damping values measured at the point of excitation on the H-structure, which could be a reasonable way of obtaining input data for a FEM prediction. However, such measured values do not describe dissipative damping only because the damping due to the transmission to the other plates is also included. The resulting energy ratios are shown in Figures 5(a) and 5(b). The calculated vibrational energy now exceeds that measured, which illustrates the difficulties in obtaining accurate input data that were mentioned in the introduction.

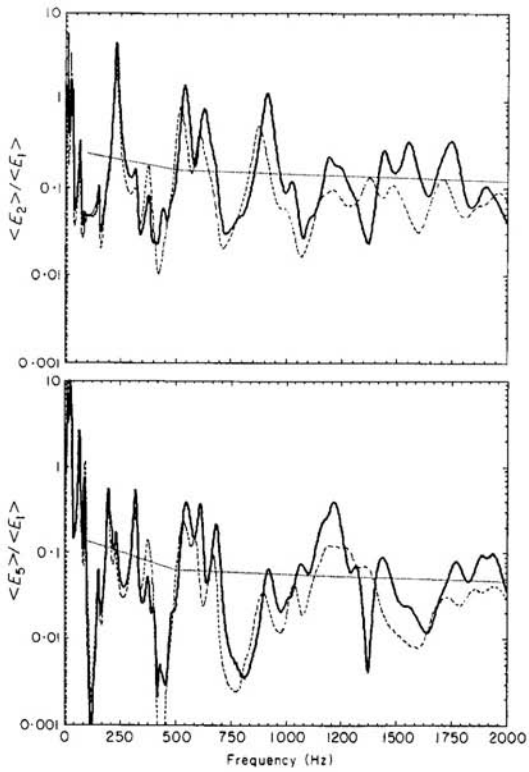


Figure 4. The energy ratios of the H-structure in Figure 3: top, $\langle E_2 \rangle / \langle E_1 \rangle$ between plates 2 and 1; bottom, $\langle E_5 \rangle / \langle E_1 \rangle$ between plates 5 and 1. ——, Experimental values in narrow bands; - - -, discrete frequency values predicted by using FEM; · · · ·, one-third octave band values predicted by using SEA [19]. Average modal damping 0·03.

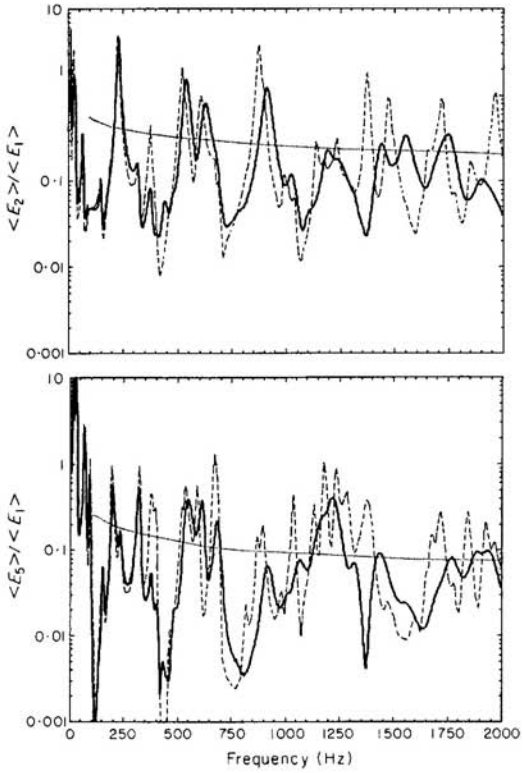


Figure 5. As Figure 4 but with the modal damping changed to $\zeta = 0{\cdot}03$ (10–350 Hz), $\zeta = 0{\cdot}02$ (350–500 Hz), $\zeta = 0{\cdot}015$ (500–800 Hz), $\zeta = 0{\cdot}01$ (800–1200 Hz), $\zeta = 0{\cdot}0075$ (1200–2000 Hz).

The energy curves (Figures 4 and 5) generally agree very well, even in narrow bands. There seem to be no severe bias errors inherent in the FEM-calculated values, but the coarse FE mesh increases the random error in the eigenfrequencies and the mode shapes. Furthermore, the random error increases in the measured as well as the FEM-calculated energy estimates for each plate—especially at high frequencies—because of the discrete number of points used in the energy estimates (equation (1)). It is observed in Figures 4 and 5 that the modal dampings for plates 2 and 5 affect the energy ratios but, according to equation (6), the estimated η_{jk}s will not vary as much. In equation (5), however, the assigned η_k of a plate k affects the calculated energy of that plate.

The plates were constrained from translations at the junctions in order to allow only the out-of-plane displacements at the junctions between plates 1 and 2 and plates 2 and 5. The resulting energy ratio between plates 5 and 1 with and without these constraints on the junctions is shown in Figure 6(a). The energy ratio fluctuates more with the translational constraints applied, probably because the modes of the plates became more local; the ratio also peaks when the energy of the excited plate (1) is low. The kinetic energy of plate 5 is shown in Figure 6(b)—the translational constraints at the junctions do not affect the average transmitted power very much. This indicates that the in-plane displacements in plate 2 are not very important to the transmission of bending waves between plates 5 and 1 in this case. However, the H-structure is small compared to the wavelengths of the in-plane waves, and therefore the in-plane displacements of plate 2 mainly add a reactive impedance to the bending wave impedances of the junctions. It

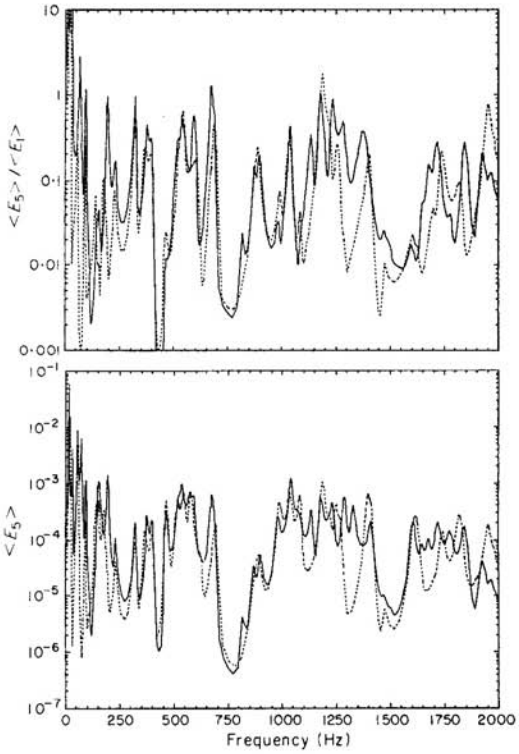


Figure 6. As Figure 5 but also with the junctions constrained from translations to prevent in-plane displacements: top, the energy ratio $\langle E_5\rangle/\langle E_1\rangle$ between plates 5 and 1, predicted with FEM; bottom, vibrational energy on plate 5 $\langle E_5\rangle$, predicted by using FEM. ——, Without the constraints; · · · ·, with the constraints.

remains to be verified that the conversions between in-plane waves and bending waves are calculated correctly with FEM in a general case.

3.2. VARIATION OF EDGE CONSTRAINTS AND MATERIAL PROPERTIES

The H-structure was used to illustrate the establishment of a limited ensemble of energy ratios that could be used to calculate a representative average of the coupling loss factor of a particular type of junction. Assuming that the coupling loss factor between plates 1 and 5 (η_{15}) is to be estimated, plates 2, 3 and 4 are considered just as a complicated coupling path. These plates could, for example, be considered to be too small to be modelled as SEA subsystems in another application. The ensemble includes seven cases with different material properties and boundary conditions: the cases described in section 3.1 and four additional cases that were calculated in order to include many different types of mode in each frequency band. More cases ought to be included in an ensemble—with systematic variations of the material properties, the sizes and the constraints at the edges—but this was too extensive to implement in this example.

Firstly, the damping values were reduced (in the same intervals as in Figure 5) from 0·025 to 0·015, and Young's modulus was increased by 20% to 5·9E9. Then, the edges parallel to the junctions were clamped, hinged or simply supported in three cases (with the same damping and stiffness as in Figure 5). The point of excitation was close to an outer corner on plate 1 in order to avoid nodal lines of any mode.

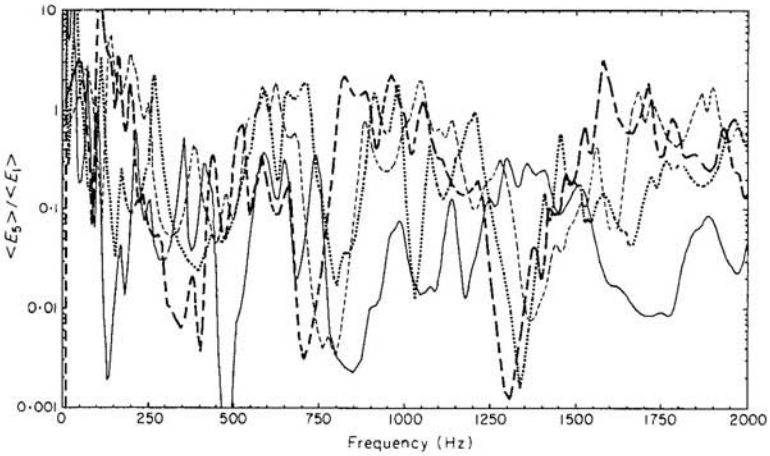


Figure 7. The energy ratios of the H-structure. The plate properties are as in Figure 5, but with some changes. The edges parallel to the junctions are constrained: - - -, clamped; · · · ·, simply supported; – – –, hinged. — —, without constraints but with ζ changed to range from 0·025 to 0·015 in the same intervals as in Figure 5 and with Young's modulus changed to $5{\cdot}9 \times 10^9$.

The constraints at the edges parallel to the junctions that were applied in the three cases gave unexpectedly high energy ratios compared to the cases with free edges, as illustrated by Figure 7. The vibration levels of the constrained plates were generally much lower than those of the unconstrained plates, which indicates that the vibrations of the constrained plates were non-resonant. The constraints resulted in a mode selection on this relatively small structure that increased the average transmission compared to the cases with free edges. Two conclusions are important in this context:

It is clear from Figures 5 and 7 that SEA (based on multi-mode interaction between the plates) does not apply to these constrained structures. The results indicate that an SEA-predicted vibration level of plates (compare with Figure 5) would have been much lower than the actual level. Nor could the energy ratios from the cases with constraints be included in the ensemble to give averages of the η_{15} because they were biased: they were not representative of an ensemble of much larger structures with the plates coupled in the same way.

Since the predicted energy ratios in Figures 4–6 seem to be accurate and agree well with the measured values and the SEA-predicted values based on ideally diffuse vibration fields, it is assumed that a future study on larger structures will give better estimates of the coupling loss factor of this type of junction.

4. CONCLUSIONS

The finite element method gave very good estimates of the vibrational energy ratios between coupled plates that were calculated at discrete frequencies in the frequency range 10 Hz to 2 kHz. The discrepancies at individual frequencies indicate that it is necessary to integrate the squared displacements over a plate and a frequency band in order to give the vibrational energy of a plate in a frequency band.

The main feature of FEM is that it is applicable to complicated structures. It is suggested that the SEA coupling loss factors can be calculated using the procedure described that is based on FEM. The calculated average η_{jk} of complicated structures can be used in statistical energy analysis of systems with junctions of the same type.

The procedure with variations of the energy ratios with respect to, for example, the different boundary conditions in order to establish an ensemble average estimate of the coupling loss factor η_{jk} was not satisfactory and will be studied in further projects at the department.

ACKNOWLEDGMENTS

I thank Professor Tor Kihlman who supervised this study, Eng. Lic. Thomas Abrahamsson who made the frame analysis with the SFVIBAT computer program and B.Sc. Roger Maxwell who made the measurements on the H-structure, all at Chalmers University of Technology. I thank Professor Jaques Roland and the staff at Centre Scientifique et Technique du Batiment who made the 4AS analysis.

REFERENCES

1. J. L. GUYADER, C. BOISSON and C. LESUEUR 1982 *Journal of Sound and and Vibration* **81**, 81–92. Energy transmission in finite coupled plates, part I: theory.
2. C. BOISSON, J. L. GUYADER, P. MILLOT and C. LESUEUR 1982 *Journal of Sound and Vibration* **81**, 93–105. Energy transmission in finite coupled plates, part II: application to an L-shaped structure.
3. A. J. KEANE and W. G. PRICE 1987 *Journal of Sound and Vibration* **87**, 363–386. Statistical energy analysis of strongly coupled systems.
4. E. K. DIMITRIADIS and A. D. PIERCE 1988 *Journal of Sound and Vibration* **88**, 397–412. Analytical solution for the power exchange between strongly coupled plates under random excitation: a test of statistical energy analysis concepts.
5. W. WÖHLE, T. H. BECKMANN and H. SCHRECKENBACH 1981 *Journal of Sound and Vibration* **77**, 323–334. Coupling loss factors for statistical energy analysis of sound transmission at rectangular structural slab joints, part I.
6. B. M. GIBBS and C. L. S. GILFORD 1976 *Journal of Sound and Vibration* **49**, 267–286. The use of power flow methods for the assessment of sound transmission in building structures.
7. P. G. CRAVEN and B. M. GIBBS 1981 *Journal of Sound and Vibration* **77**, 417–427. Sound transmission and mode coupling at junctions of thin plates, part I: representation of the problem.
8. B. M. GIBBS and P. G. CRAVEN 1981 *Journal of Sound and Vibration* **77**, 429–435. Sound transmission and mode coupling at junctions of thin plates, part II: parametric survey.
9. T. KIHLMAN 1967 *Report from Byggforskningen, Stockholm* 9/67. Transmission of structure-borne sound in buildings. (In English.)
10. L. CREMER, M. HECKL and E. E. UNGAR 1973 *Structure-borne Sound.* Berlin: Springer-Verlag.
11. K. J. BATHE 1982 *Finite Element Procedures in Engineering Analysis.* Englewood Cliffs, New Jersey: Prentice-Hall.
12. *ABAQUS Theory Manual* 1987 Hibbit, Karlsson & Sorensen, Inc. 100 Medway Street, Providence, Rhode Island 02906, U.S.A.
13. R. LYON 1974 *Statistical Energy Analysis of Dynamical Systems—Theory and Applications.* Cambridge, Massachusetts: M.I.T. Press.
14. D. A. BIES and S. HAMID 1980 *Journal of Sound and Vibration* **70**, 187–204. *In situ* determination of loss and coupling loss factors by the power injection method.
15. B. L. CLARKSON and M. F. RANKY 1984 *Journal of Sound and Vibration* **94**, 249–261. On the measurement of the coupling loss factor of structural connections.
16. F. J. FAHY 1974 *Shock and Vibration Digest* **6**(7), 14. *Statistical energy analysis—a critical review.*
17. *SFVIBAT II—A Computer Program For Space Frame Vibration Analysis.* Chalmers University of Technology, S-412 96 Gothenburg, Sweden. (In Swedish.)
18. C. SIMMONS 1988 *Proceedings of the Nordic Acoustical Meeting* 88, 207–210. FEM-calculations of the transmission of structure borne sound through junctions between plates.
19. *4AS—a Computer Program for SEA Calculations* 1988 Centre Scientifique et Technique du Batiment, 24 rue Joseph Fourier, F-38400 St-Martin-d'Herès, France.
20. C. H. HODGES, P. NASH and J. WOODHOUSE 1987 *Applied Acoustics* **22**, 47–69. Measurement of coupling loss factors by matrix fitting: an investigation of numerical procedures.
21. E. LUZZATO and E. ORTOLA 1988 *Journal of Sound and Vibration* **123**, 189–197. The characterization of energy flow paths in the study of dynamic systems using SEA theory.

Paper II

Manuscript submitted to Noise Control Engineering Journal,
Editor-in-Chief Courtney Burroughs, courtneyatncej@verizon.net

Measurements of structure-borne sound from building service equipment by a substitution method – inter-laboratory comparisons

Krister Larsson[1]

Christian Simmons[2]

INCE subject classifications, suggestions: *12.4.6, 21.7, 51.6, 51.8, 51.9, 72.2.1,*

A pilot project with an inter-laboratory comparison (round robin) has been performed, where a modified heavy-duty washing machine has been circulated for tests among 7 laboratories. The main goal of this pilot project was to find out whether a simple substitution method could be applied to estimate the structure-borne sound source strength of some typical building service equipments in the field. The vibration levels of a heavy low mobility test floor, measured when a machine with high internal mobility operates on this floor, are compared to the vibration levels obtained on the same floor when the standardized tapping machine (ISO 140-7) operates in place of the test machine. These vibration level differences obtained on a heavy floor may be used to estimate the actual machine force and the characteristic power on other heavy floors by comparison to the forces and powers of the standardized tapping machine, according to the new European standard EN 12354-5. This EN standard also describes how sound pressure levels in a nearby room may be deduced from the measured data. In its simplest form, this can be made in the same way as for floorings, i.e. first calculating the normalized impact sound pressure level (EN 12354-2) and then subtracting the force level difference of the actual machine compared to the tapping machine.

[1] SP Technical Research Institute of Sweden, Box 857, SE-501 15 Borås, Sweden.www,sp.se krister.larsson@sp.se
[2] Luleå univ. of technology and Simmons akustik & utveckling, Krokslätts Fabriker 1, SE-43137 Mölndal, Sweden. www.simmons.se christian.simmons@euromail.se

1. INTRODUCTION

Structure-borne sound (SBS) from building service equipment is an important issue to manufacturers of such equipment as well as developers, contractors and consultants. SBS may cause unexpected indoor noise problems in modern apartment buildings and in public premises such as hospitals, schools etc. These problems might even increase in the future because of the increased use of light-weight building structures, e.g. timber joist floors, where normal structure-borne sound insulation solutions become complicated. It is common to add sound insulation to walls and slabs (linings) to prevent vibrating structures to radiate sound. The lack of source data has the effect that building constructions are not optimized but either exaggerated or underperforming.

A new European standardized method (EN 15657-1:2009, ref. 1) is now available to determine the source strength of structure-borne sound sources with high mobility operating on a reference concrete plate under laboratory conditions. Another new European standard (EN 12354-5:2009, ref 2). may be used to calculate the propagation of SBS and its radiation of sound in nearby rooms. The laboratory method is based on research by members of the CEN technical committee TC 126/WG 7 (ref 3, 4). However, there is little practical experience in the field with these methods. To document SBS performance of machinery or vibration insulation solutions in the field, a simple and robust measurement method is needed. The lack of practical methods is a major drawback for the building industry, particularly to manufacturers of building service equipment such as HVAC systems, elevators, laundry machines, sanitary equipment and kitchen furniture. In this paper, a practical method has been tested at several sites, according to principles for substitution measurements of the source strengths described in EN 12354-5.

In course of preparing a pilot study, there were critical arguments against the reproducibility of a substitution method. The source strength determined either by comparison to a tapping machine (standardized in EN ISO 140) or determined by a reception plate method (EN 15657-1), could be strongly affected by different modal vibrations of the supporting floor. If so, this would alter the source strength in a building, as compared to the strength determined in the laboratory. This relation of performance in the laboratory data to performance *in situ* must be well known in order to make the test results from the laboratory applicable in practice. Therefore, it was necessary to perform a round robin test, including dedicated impact sound laboratories as well as realistic buildings with a variety of heavy-weight floor constructions.

There may be a need for several methods with different precision grades and measurement resources, suitable for laboratories as well as in situ. This paper is only one-step towards this goal; more research has to be conducted in the future.

To study the feasibility of the substitution method, one structure-borne sound source (with three different bases and four modes of operation) was circulated for tests at 5 Nordic and 2 European laboratories. The main purpose was to evaluate the characteristic spread of results among various laboratories. Some of the participating laboratories were not familiar with the draft standards mentioned above, since the measurement methods proposed therein are not typical for building acoustic laboratories. Thus, it was decided to assign one test leader to bring the test object and to monitor the measurements in each laboratory. This presence may have influenced the measurement results.

The pilot study was divided into three steps:

- initial tests were made at SP, in their reference impact sound laboratory as well as in 2 nearby spaces to evaluate if there were any interpretation problems of the provisional testing instructions. After this initial study, some of the participating laboratories commented on the findings and suggested improvements.
- circulating one typical source for test. The source used for this inter-laboratory comparison was a modified heavy-duty laundry machine with 4 fixed speeds (computer controlled) and variable structural mobility (as is described in the next clause). This machine may be regarded as a typical source of vibration in this context, i.e. the results may be applicable to other types of equipment with similar framed thin steel structures and operating frequencies, e.g. HVAC units, elevators, water pipes etc. This assumption is based on experience of the types of steel

frames used for such machinery, which is often reasonably similar to the washing machine used as test object. Studies by Mayr et al (ref 3) suggest that the mechanical mobility of weak steel frames tend to be rather similar, which is also suggested in EN 12354-5.

- extending the range of floors by means of one light weight floor inserted in an impact sound laboratory (with suppressed flanking transmission), as well as one timber joist floor placed on top of a reference concrete floor. This “mock-up floor” test was made in a similar way as is described in the Nordtest report TR 488 (Kartous and Jonasson, ref 5) and included in an informative annex of ISO 140-11. However, the joists of our mock-up floor were supported differently to the TR 488 floor. This change was made for the purpose of evaluating performance of structure-borne sound sources vibrating at low frequency, and to estimate the efficiency of vibration insulation products from the manufacturer, when these sources are mounted to light weight floors of similar dimensions. Experience tells, that additional insulations may even cause deteriorations, i.e. increase the structure-borne sound transmission to the supporting building structure, when this structure is comparatively weak.

The results of this inter-laboratory comparison on different floors (slabs) may not be representative for other types of source with considerably lower source mobility, e.g. diesel engines, cooling compressors or electrical motors with very rigid structures or footings. The applicability should be restricted to equipment with weak frames made from wood or steel, placed on concrete floors with a minimum thickness of 10 cm. If additional tests are made on a light-weight structure (with high floor mobility) as is suggested in the proposed measurement method (ref. 6), the results are only relevant for such floors with the specified source. Indications on source mobility for various types of source or receiver structures are given in an annex to the standard EN 12354-5.

2. TEST OBJECT

The source used for this inter-laboratory comparison is a modified washing machine, Electrolux Laundry Systems type “Wascator 465H”, intended for 6,5 kg dry load. This heavy duty laundry machine is intended for common laundry spaces in apartment buildings, stores, pre-schools, hospitals etc. The machine has 4 fixed speeds and may be used with variable bases (foundations). These bases imply different structural mobility of the source (c.f. figure 1). This machine is somewhat larger than typical household machines (its dimensions being HxDxW 112 x 69 x 72 cm and its weight being 154 kg). The drum was loaded with a steel plate (1,5 kg) being fixed eccentrically, i.e. to one side of the drum (c.f. figure 1d). The drum and driving motor are internally suspended on soft steel springs and friction dampers.

The machine was placed on top of three different bases in order to change the source mobility, see figures 1a-1c. This was achieved by means of 4 hand-operated jacks (acting as feet in one of the three cases) and a fork lift that made the changes of base efficient. The machine was not fixed to the bases, nor to the test floors. After each change of base, the balance and horizontal positioning of the machine and the feet were adjusted. The machine was operated at four fixed speeds (on each base type), as controlled by an internal microcomputer: 720, 840, 960 and 1080 rpm (12, 14, 16, 18 Hz). The unbalance forces were quite noticeable at these speeds (with the steel plate eccentric load). This load case may occur in practice from time to time, and the machine has been designed to handle such unbalances without interrupting or pro-longing the washing program. House-hold machines are often designed differently, where its microcomputer measures the unbalance force and tries to redistribute the washing load until the unbalance forces are minimized before the drum is accelerated. This takes additional time and makes the speed changing without control. For this reason, such a machine would not have been practical for this study, albeit considerably easier to move in and out from the laboratories (!)

3. TEST FLOORS

In some laboratories, tests were made on several floors. The floors used for tests are listed in a random order.

A. 16 cm massive concrete floor, 4,0 x 3,4 m^2, supported on 3 masonry walls (340 kg/m^2), one side free (with a light weight stud-and-plasterboard wall beneath). Thin linoleum carpet laid on the floor (without foam layer and without glue). Reverberation room under the plate, intended for impact sound reduction tests according to the standard ISO 140-8

B. 10 cm massive concrete floor, 2,8 x 2 m^2, 4 free sides. The plate is supported by elastic pads to serve as a 'reference plate' according to the standard EN 15657-1

C. 10 cm massive concrete floor, 250 kg/m^2, 3,15 x 3,15 m^2, on 40 cm concrete frame and walls. Reverberation room under the plate, intended for impact sound reduction tests according to ISO 140-8

D. 2x2 cm OSB floor boards on 45x145 mm wooden joists spaced 0,8 m, no ceiling under the joists, joists supported by 40 cm concrete frame and walls. Reverberation room under the plate, intended for impact sound reduction tests according to ISO 140-11

E. 10 cm massive concrete slab with tile flooring, supported by 20 cm expanded polystyrene thermal insulation on a crushed rock ballasting on soil bed, 9 x 7 m^2. The edges of the plate have an increased thickness (30 cm) to carry the load of the light weight walls and roof

F. 30 cm massive concrete floor on 50 cm concrete beams spaced 5,6 m, the overall plate size being> 600 m^2. Tests were made in the middle of one floor section (between the beams, 7,4 x 5,6 m^2

G. 16 cm massive concrete floor, 3,2 x 4,2 m, on a 30 cm concrete frame and concrete walls, the room being supported by steel springs (with a low loss factor). Reverberation room under the plate, intended for impact sound reduction tests according to ISO 140-8 (ref 7), without any structural connection to the test floor

H. 10 cm massive concrete floor, 7,5x5,7 m, 4 free edges, suspended on cork/rubber vibration insulation (f_0 <20 Hz), light weight walls and roof load carried by the edges of the floor

I. 14 cm massive concrete floor (360 kg/m^2) 2,9 x 3,8 m^2, on 4 masonry walls. Reverberation room under the plate, intended for impact sound reduction tests according to ISO 140-8

J. 15 cm massive concrete slab 3,3 x 3,3 m on heavy concrete frame and walls. Reverberation room under the plate, intended for impact sound reduction tests according to ISO 140-8

K. (Not used.)

L. (Not used.)

M. 2,2 cm particle board screwed (not glued) to wooden joists 45x195 mm, spaced 600 mm, width 2,4 m, length 3,6 m.

N. 2,2 cm particle board screwed (not glued) to wooden joists 45x195 mm, spaced 600 mm, width 2,4 m, length 2,5 m. Floor M was accomplished by adding a third joist support to the floor L (a wooden lath between the joists and the concrete floor)

4. MEASUREMENTS

4.1. Measurement setup

In the inter-laboratory tests, the washing machine was operated at 3 positions (except for 4 positions on floors A and B, 2 positions on floors C and D). One source position was located close to a corner of the test floor and the others were placed asymmetrically in the middle of the test floor (except for floor E where all source positions were in the middle region of the

large floor since there were no corners available). The standardized tapping machine was placed in 2 positions in the center of each position used for the washing machine, the 2 positions being at right angles following its diagonal lines. The accelerometers (4 positions) were placed in the middle of the floors, avoiding their symmetry lines and diagonal lines, on at least 0,5 m distance from each other and at least 0,2 m away from the any source position or edge. On floors A and B, 7 positions were used for the accelerometers. Figure 2 shows the floor H setup as an example.

4.2. Measurements

- Measurement equipment: 2-8 accelerometers fixed to the floor surface and connected to third octave band sound level meters (real time analyzers) that comply with requirements in ISO 140-4 and ISO 10848-1
- The velocity levels of the background (no source in operation) and for maximum excitation (with tapping machine) were determined in 4-8 positions and compared to the vibration levels with the source operating, to determine the upper and lower limits of measurement (i.e. the effective dynamic range).
- Test object and modes of operation, c.f. clause 1
- Measurement time: 32 seconds after 30-60 seconds starting and settle time for the washing machine, i.e. each measurement was made at a constant speed
- All data presented for the inter-laboratory comparison below refer to logarithmic spatial and time averages of 4 speeds, taken over all source and all accelerometer positions for each source. This is referred to as the ISO-average since it is similar to the procedure in ISO 140-8 (ref. 7).
- In the final method NORDTEST NT ACOU 117 (ref 6), another type of averaging is applied, which is referred to as the NT-average. This is discussed in clause 5.4.

5. RESULTS

5.1. Initial tests with washing machine on its ordinary feet

As a part of the preparation of the inter-laboratory test round, some sample measurements were made at SP on 3 concrete floors with various thickness and supports. Figures 3a)-f) illustrate the spread of acceleration levels (taken as the spatial logarithmic average of 4 accelerometers) for 8 source positions of either the standardized tapping machine or the washing machine. In this test (only), the washing machine was operating on its ordinary stiff feet (made by a short thin steel rod and a plastic washer), i.e. the external machine bases described in clause 1 were not used for these initial tests.

5.2. Inter-laboratory comparisons on 9 concrete floors with 3 modified bases

The results of the inter-laboratory measurements are summarized in figures 5a-5c. The figure 5d shows vibration levels using the tapping machine on 5 concrete floors. The figures 6 show vibration level differences for each type of base on each floor. For anybody who is interested in the detailed results, the authors may forward an MS Excel file with all vibration levels of each floor and each test object. Please direct such a request to the authors, with a short explanation of its purpose.

The figures 5b and 5c indicate, that the standard deviations of results from the different laboratories are less than the difference in performance of the machine, put on 3 different bases. The difference is reasonably stable at the lowest frequencies compared to the higher. For practical purposes, the Nordtest method (NT ACOU 117) includes a safety margin of one standard deviation to be subtracted from the average vibration level difference, in order to coop with the uncertainty of this field method.

As can be seen in the figure 5d, the vibration levels from the tapping machine are considerably weaker below 20 Hz than at higher frequency. This may be explained by the periodic motion of the tapping machine, where the average time between hammer impacts is 0,1s. Thus, high energy may be expected at 10 Hz and the multiple frequency bands (20, 31, 40.. Hz), but the intermediate third octave bands 12 Hz, 16 Hz, 25 Hz etc. would be expected to contain considerably less energy. This also explains parts of the large uncertainty at 16 Hz. Thus, the measurement range should be limited downwards to say the 25 Hz third octave band. Results given in this section are plotted down to 20 Hz or even 12 Hz, but 25 Hz is adopted in the NT ACOU 117 method (ref 6) to be the lowest frequency of measurement being reported.

5.3. Sample tests on 3 wooden floors with 1-3 modified bases

The substitution method described in the previous clauses refers to concrete floors, where the source mobilities of the machine and its bases may be assumed much higher than the mobility of the floor. It was highlighted by the manufacturers, that difficult sound problems arise when their equipments are operating on light weight floors. Thus, it was decided to make some tests to study what happens when the same machine/base is moved from a concrete floor to three types of timber joist floor. See figures 4. The mobility of such floors may be expected to match the mobility of the test object at some frequencies and thereby increase the structure borne sound power input to the wooden floor. This increase was expected to be underestimated by the comparisons to the tapping machine made on a concrete floor, as is described by theoretical expressions in EN 12354-5.

Figures 7 shows the spatially logarithm-averaged vibration levels measured with the test object (on 3 bases) as well as the tapping machine. The differences between the spatially averaged vibration levels of the test objects and the tapping machine are significantly lower at low frequencies, compared to results obtained on a concrete floor with the same equipment and operating conditions. This result confirms the experience of vibrations of light floors mentioned above.

The different spectral shapes of figure 7c are assumed to be caused by some of the accelerometers to be placed far away from the source on floor D, with 2 beams inbetween. This is known to cause spatial decay of vibration levels on timber joist floors. Floors M and N of the figures 7 clearly demonstrate the effect of mobility matching at low frequencies, i.e. the prerequisite for the force source approximation is obviously not valid. If it would have been so, the vibration level difference would have been the same irrespective of floor mobility.

5.4. Influence of the type of spatial averaging

Two different types of averaging of the results and the scatter between different source positions have been investigated, as shown in figure 8 and 9 respectively. The first type of averaging of the vibration levels of the receiving structure was used to plot the figures 2-5 . Each average was taken as the logarithm-average of all source and all receiver positions used for each type of source, then their difference was computed (i.e. between the vibration levels of the floor when the tapping machine operated on the floor, then the test object). This is referred to as the “ISO-average” in the figures 8 and 9, since it is used in the ISO 140-8. With a second type of averaging, the vibration level difference of each accelerometer is computed from the tapping machine acting and then from the test object acting. The average is taken as an aritmethic average of all such differences. This type of averaging is referred to as the “NT-average” in figures 8 and 9. In the method NT ACOU 117 (ref 6), the vibration level difference is

ΔL_s

for a given third-octave band, the vibration level difference on the test floor for each transducer, taken when the test object is operating and then with the substitution source operating in the same position.

$$\Delta L_s = L_{s,0} - L_s \text{ dB}$$

where

$L_{s,0}$ = vibration level at a transducer position on the test floor when the substitution source is running

L_s = vibration level at the same transducer position on the test floor when the test object is running

The “ISO”- method could be applied when a diffuse reverberant field is available (compare with measurement of airborne sound power according to ISO 3741) and the “NT”-method may be more appropriate when a diffuse reverberant field is not available (compare with for instance ISO 3747). *However, this is only a hypothesis and it remains to be proved*. Figures 8 show the level differences between the tapping machine and the washing machine used as test object in this study, using the one foundation and one fixed speed, comparing and both methods of averaging.

6. CONCLUSION

The results of the inter-laboratory measurements are encouraging with respect to the possibility to establish a field method for the determination of structure borne sound from building service equipments. The spread of results call for some statistical analysis to be applied to a measurement result, such that the final result represent e.g. the 10-20% highest level that may be expected on any kind of floor of a similar type as being measured. For light weight floors, separate measurements must be made and the difference in vibration levels may only be referred to for similar types of floor.

7. ACKNOWLEDGEMENTS

The work presented in this paper was sponsored by the Nordic Innovation Centre in Oslo and the Swedish Concrete Federation in Stockholm, which are hereby gratefully acknowledged. We also thank the participating laboratories: Lieven de Geetere, Bart Ingelaere at the Belgian building research institute; Jonas Brunskog at the Technical University of Denmark; Eddy Gerretsen at TNO Acoustics laboratory in the Netherlands; Sigurd Hveem and Terje Retteråsen at SINTEF Building and Infrastructure in Norway. The authors also thank prof.ir. Eddy Gerretsen for his continuous advice given during the project and Electrolux Laundry Systems for the washing machine used a a test object.

8. REFERENCES

[1] European standard EN 15657-1:2009: Acoustic properties of building elements and of buildings - Laboratory measurement of airborne and Structure-borne sound from building equipment - Part 1: Simplified cases where the equipment mobilities are much higher than the receiver mobilities, taking whirlpool baths as an example. Prepared by CEN/TC 126/WG 7.

[2] European standard EN 12354-5: Building acoustics — Estimation of acoustic performance of building from the performance of elements — Part 5: Sounds levels due to service equipment. Prepared by CEN/TC 126/WG 2.

[3] Consideration of vibration sources in buildings on a power basis. Andreas R. Mayr, Barry Gibbs, and Heinz-Martin Fischer. Proceedings of the 13th int. congress on Sound and Vibration, Vienna in July 2-6 2006.

[4] On the use of a single equivalent receiver mobility in lightweight buildings. Gibbs, B. Proceedings of the 19th int. congress on acoustics, Madrid in September 2-7 2007.

[5] A Simplified Method to Determine Impact Sound Improvement on Light-Weight Floors. Jonasson H, Kartous M. Nordtest report NT tec 488, project 1544-01. Nordic innovation centre 2002. ISSN 0283-7234.

[6] Larsson K, Simmons C. Technical report "NT tec 616 / TR616 Determination in the field of structure-borne sound source strength of building service equipment" and theNordtest method description "NT ACOU 117 - Determination in the field of structure-borne sound source strength of building service equipment" (ISSN 0283-7234, Oslo 2009) are available (free) at: http://www.nordicinnovation.net

[7] ISO 140-8 Acoustics -- Measurement of sound insulation in buildings and of building elements -- Part 8: Laboratory measurements of the reduction of transmitted impact noise by floor coverings on a heavyweight standard floor. www.iso.ch

Figure 1: Washing machine Electrolux Laundry Systems type Wascator 465H, on a) the framed base with a MDF plate on 4 hand-operated jacks, b) the concrete filled steel plate base (200 kg) resting on massive steel cylinders, c) the same concrete base resting on Sylomer® soft polymer cylinders (f_0 12 Hz), d) the drum and the eccentric load (a 1,5 kg steel plate screwed to the side of the drum)

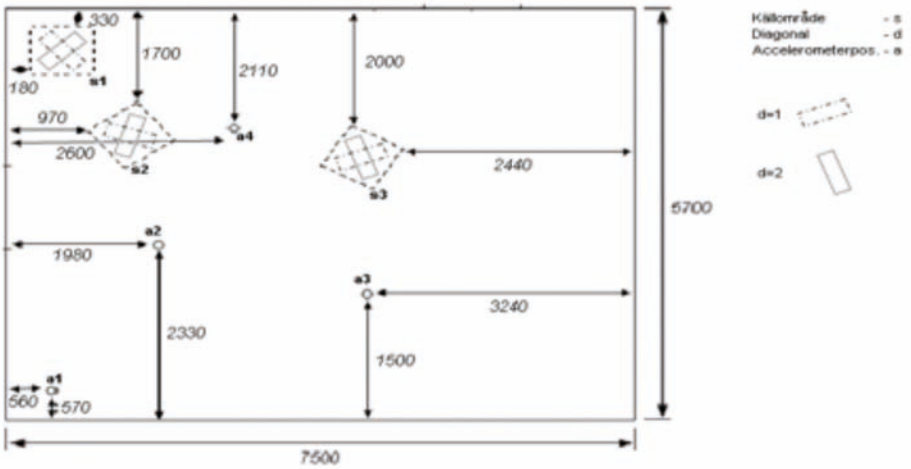
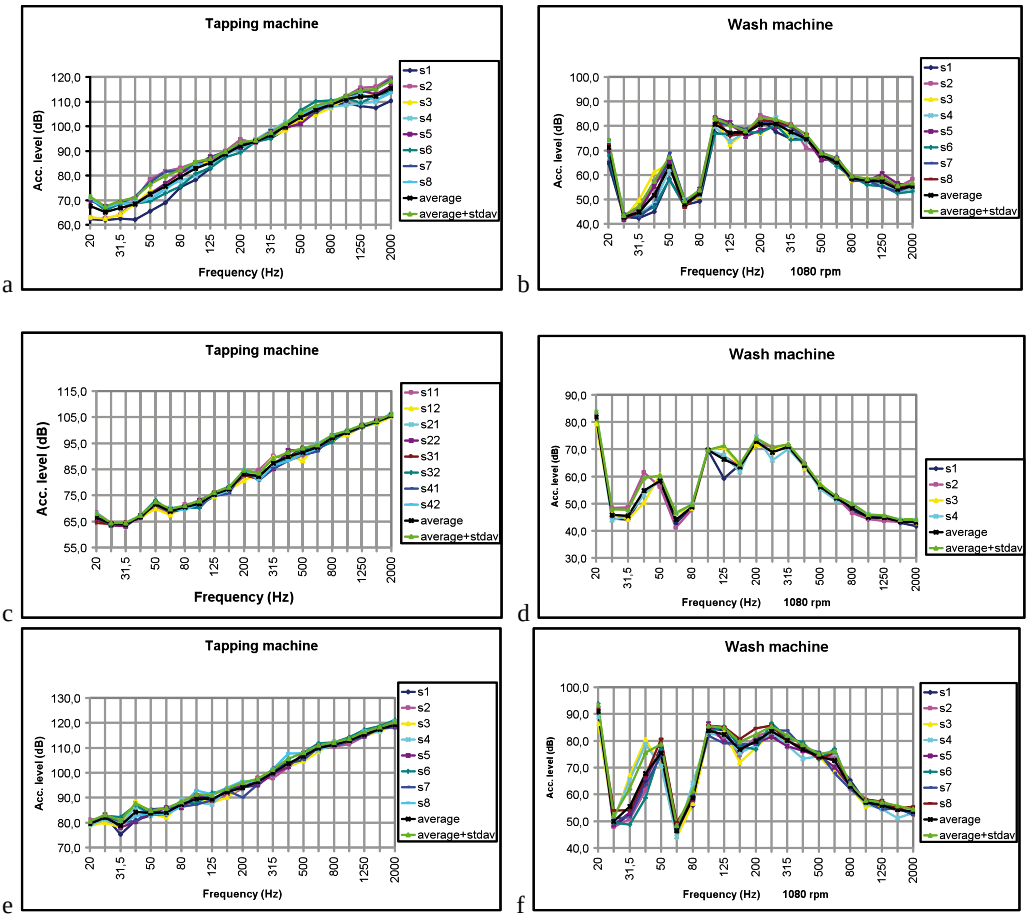


Figure 2. Example of test setup (floor H). sX denotes source positions, aY denotes accelerometer positions, d1 and d2 shows orientation of tapping machine on the diagonals of each source position.



Figures 3 a-f. Measured acceleration levels on three concrete floors with different thickness and support. Scatter of results for various source positions, with a) c) e) the standardized tapping machine (according to ISO 140-8 and with b) d) f) the washing machine, for floors E, F and G, respectively. The washing machine was placed on its ordinary stiff feet made by steel and plastic (i.e. without the bases described in clause 3.1), operating at the maximum speed 1080 rpm.

Figures 4. Example of a mock-up light weight timber joist floor attached to the surface of a concrete floor in an impact test laboratory. It is used for additional tests of vibration level differences where the vibration of the test object is compared to the levels from the substitution source.

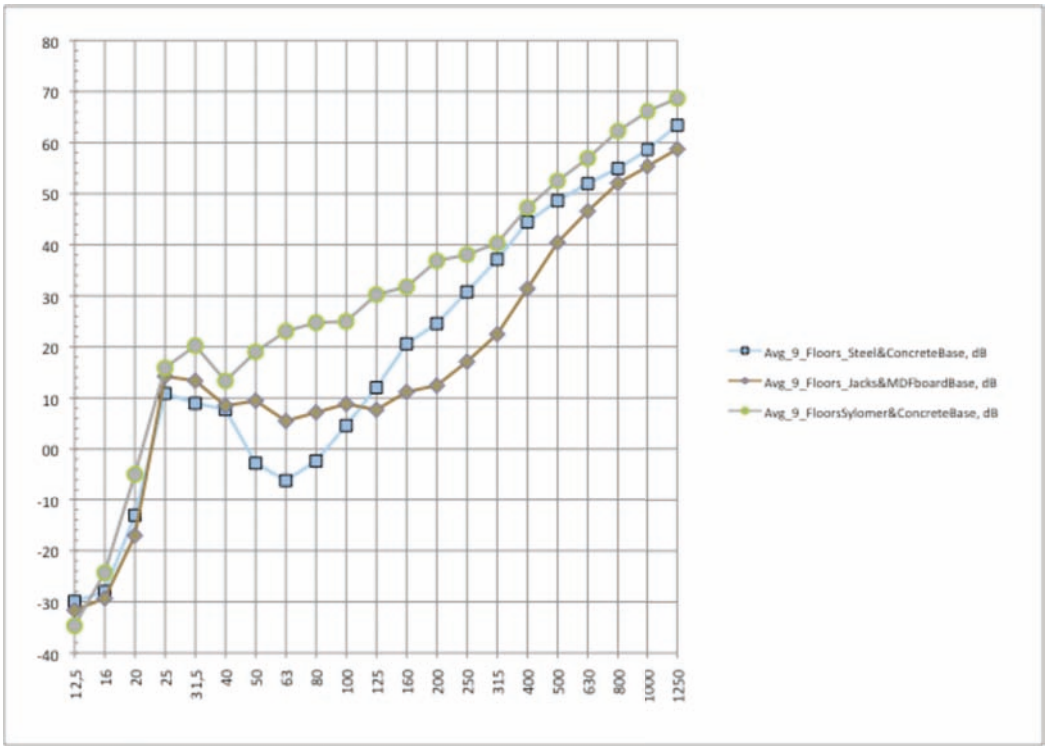
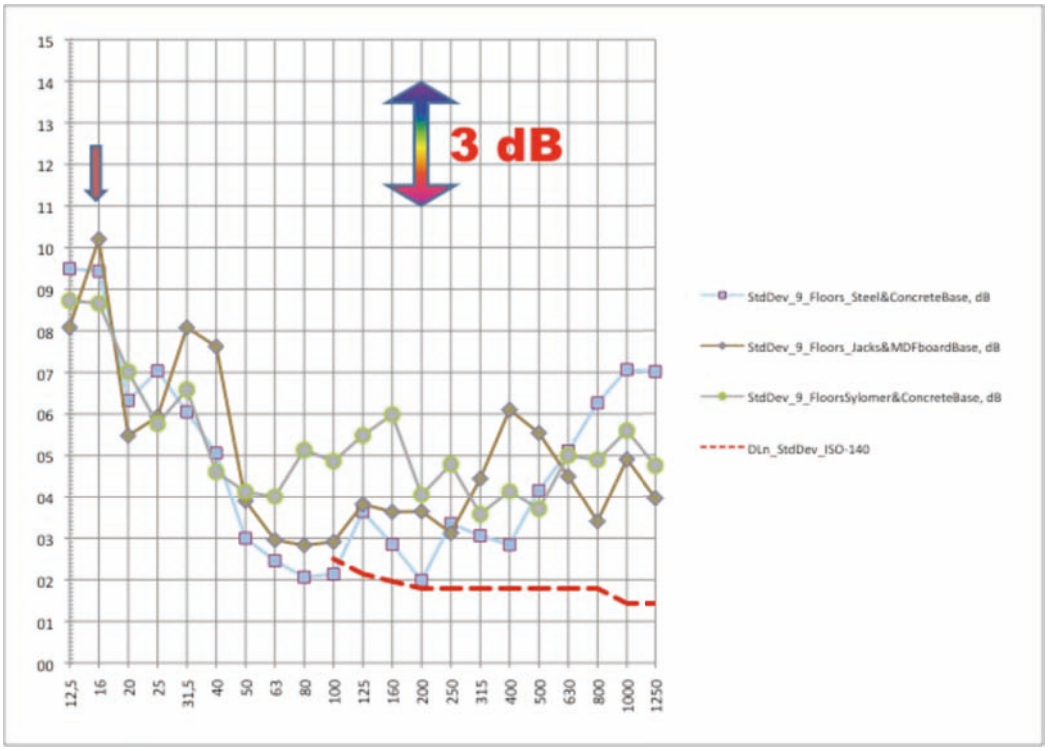


Figure 5a): Differences between the spatially logarithm-averaged vibration levels of the standardized tapping machine and the washing machine, put on three types of base, on 9 concrete floors. Average of 4 speeds 720-1080 rpm (12-18 Hz.



)Figure 5b): Standard deviation of vibration level differences. Legend, see figure 5a.

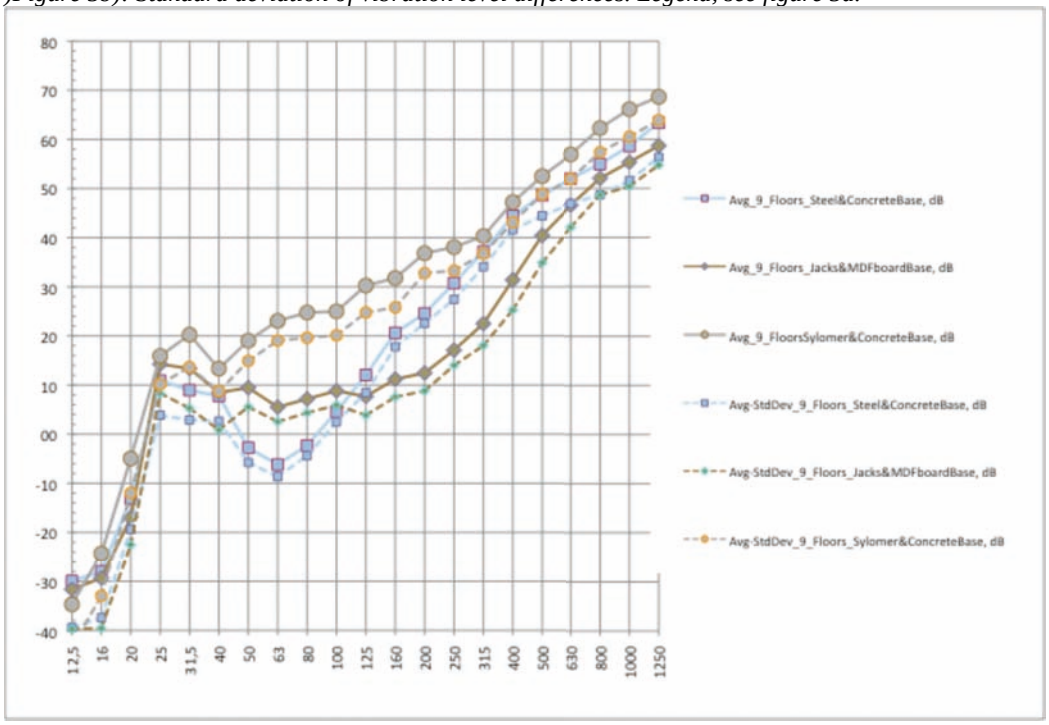


Figure 5c. (—)-) the vibration level differences from figure 5a, (- - -) the vibration level differences (from figure 5a) reduced by one standard deviation (figure 5b)

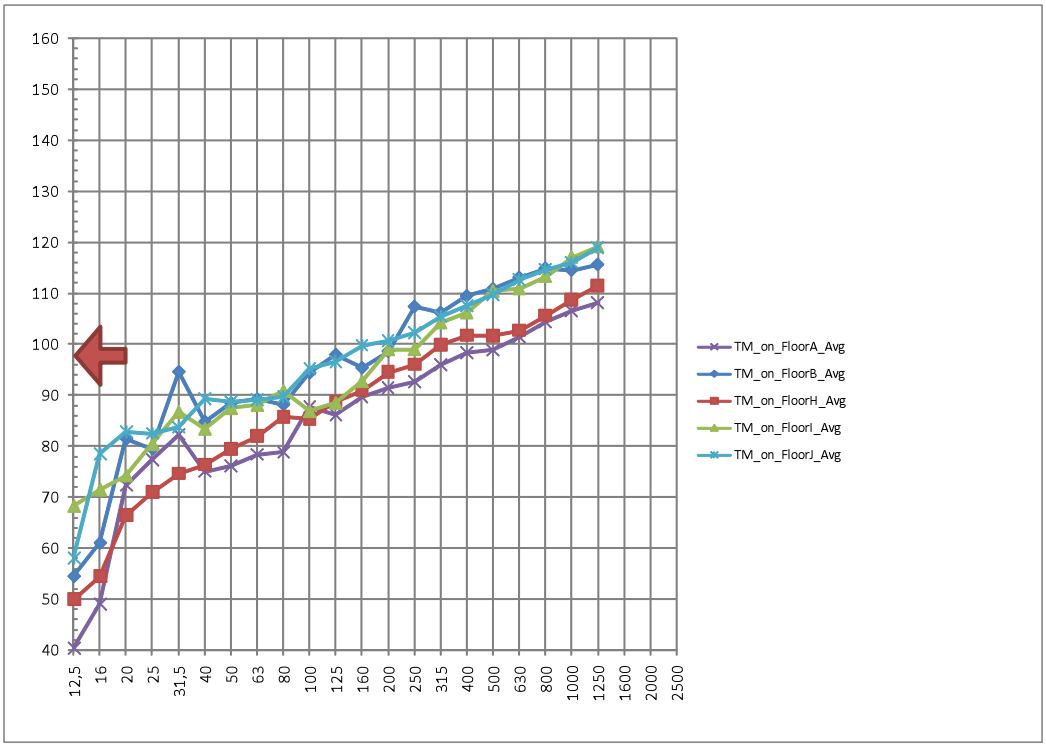


Figure 5d. Vibration levels from the tapping machine on 5 concrete floors. Below 20 Hz, the energy is reduced significantly compared to the higher frequency bands.

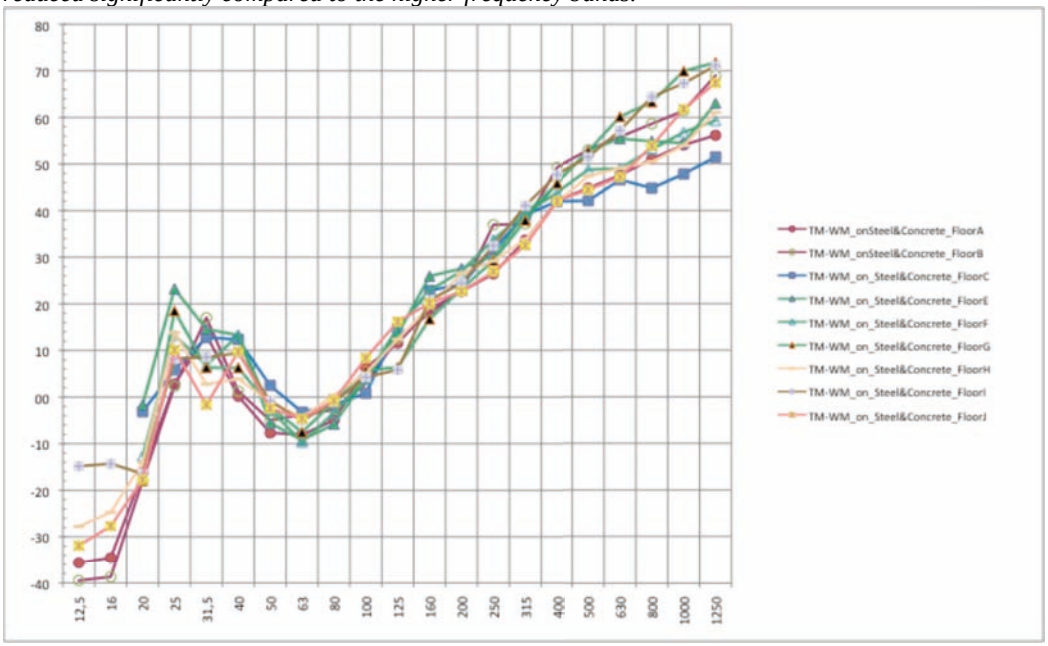


Figure 6a. Differences between the spatially logarithm-averaged vibration levels of the standardized tapping machine and the washing machine, put on the Steel&Concrete base on steel footings, measured on 9 concrete floors. Average of 4 speeds 720-1080 rpm (12-18 Hz).

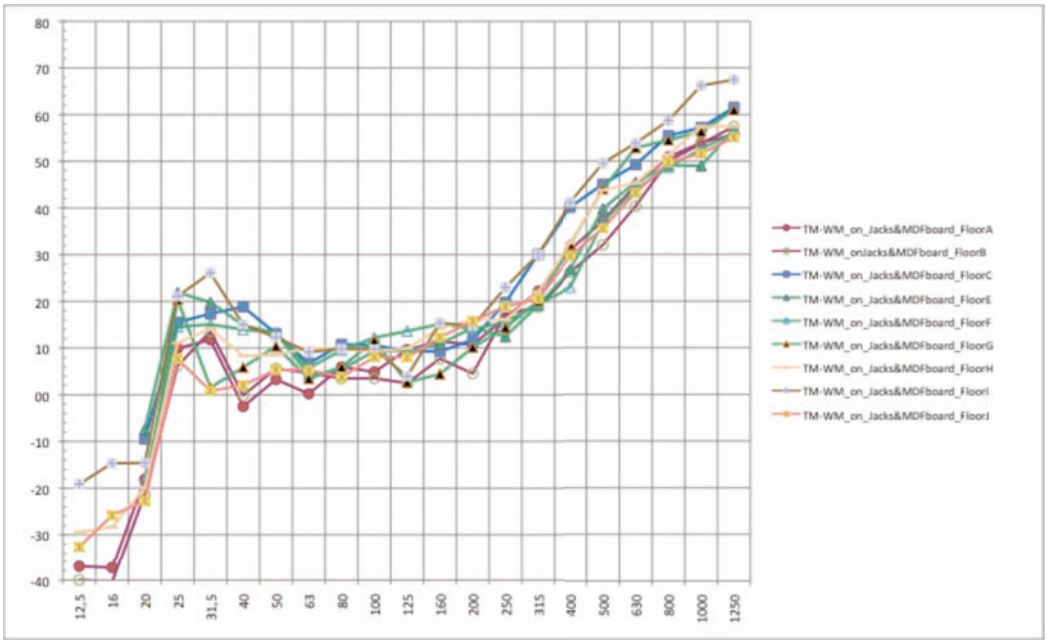


Figure 6b. As for 6a, washing machine put on the MDF-board base on 4 screw jacks

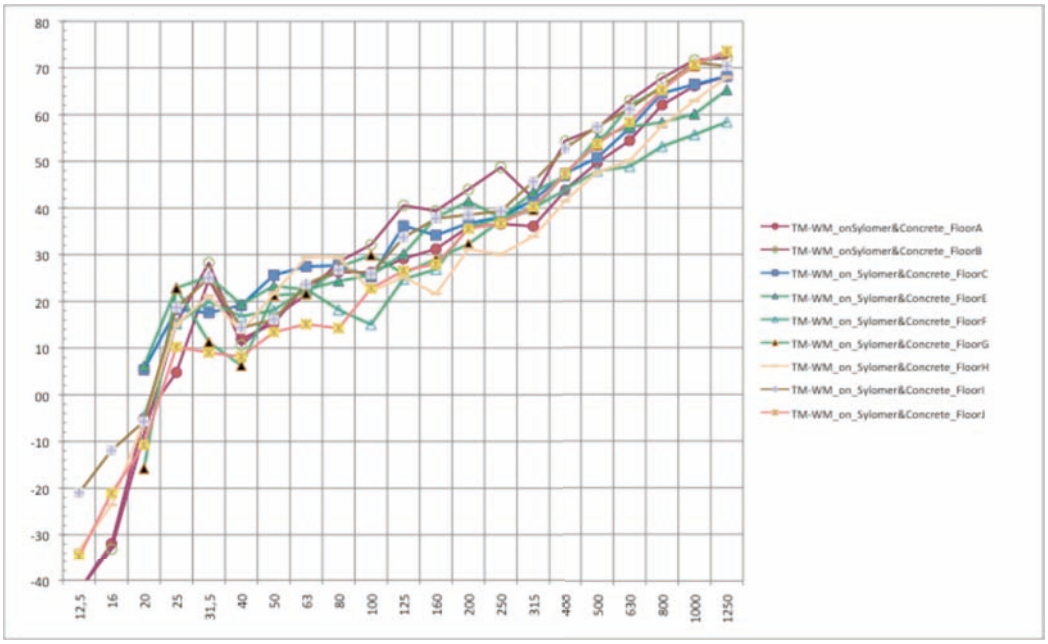
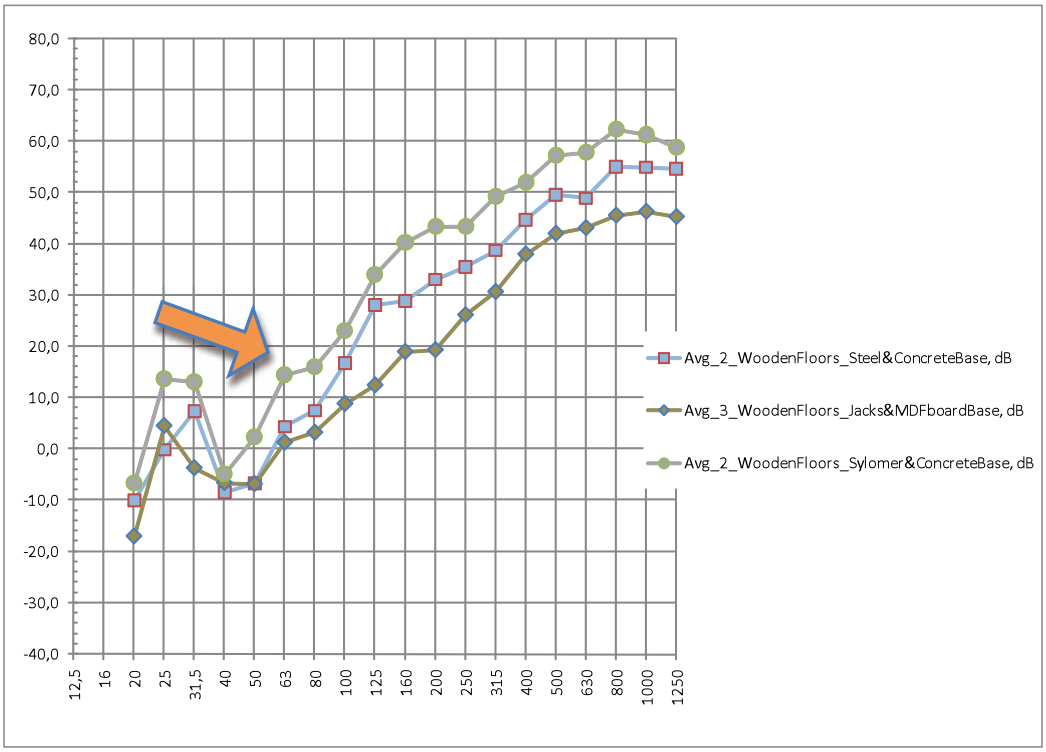


Figure 6c. As for 6a, washing machine put on the Steel&Concrete base on Sylomer® footings



Figures 7a: Differences between the spatially averaged vibration levels of the standardized tapping machine and the washing machine, put on three types of base (floors M, N), on 2-3 timber joist floors. Floor D measured with jacks/MDF-board only. Average of 4 speeds 720-1080 rpm. Up to 50 Hz, the test object may produce higher vibration levels than the tapping machine (negative differences).

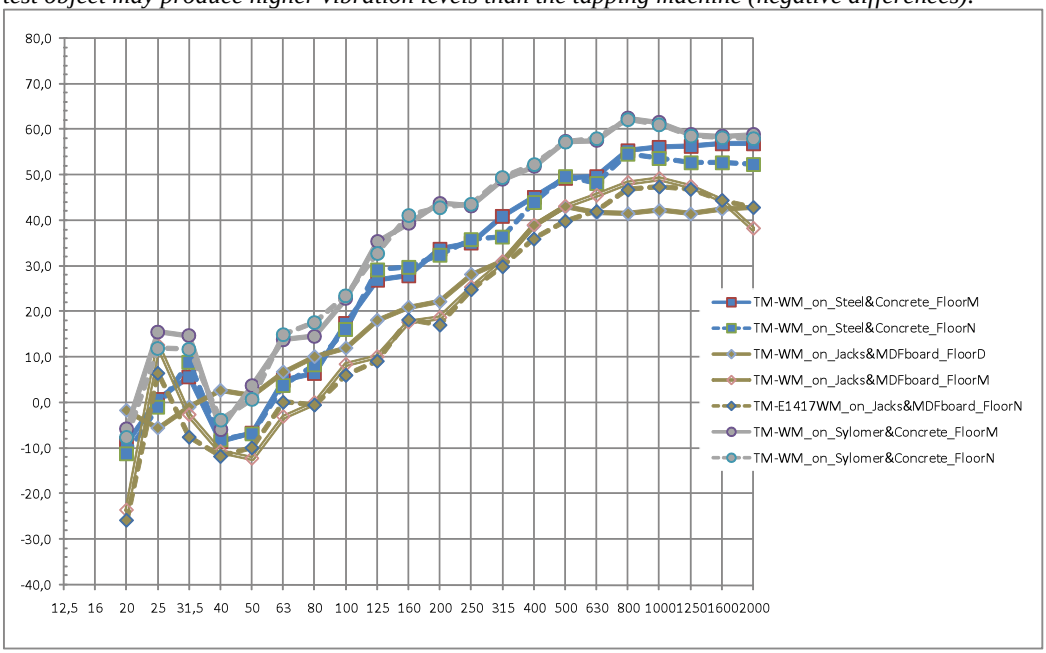


Figure 7b): As for figure 7a, with all measurement cases included. Standard deviations could not be calculated (too few samples). The vibration level difference is significantly lower at low frequencies.

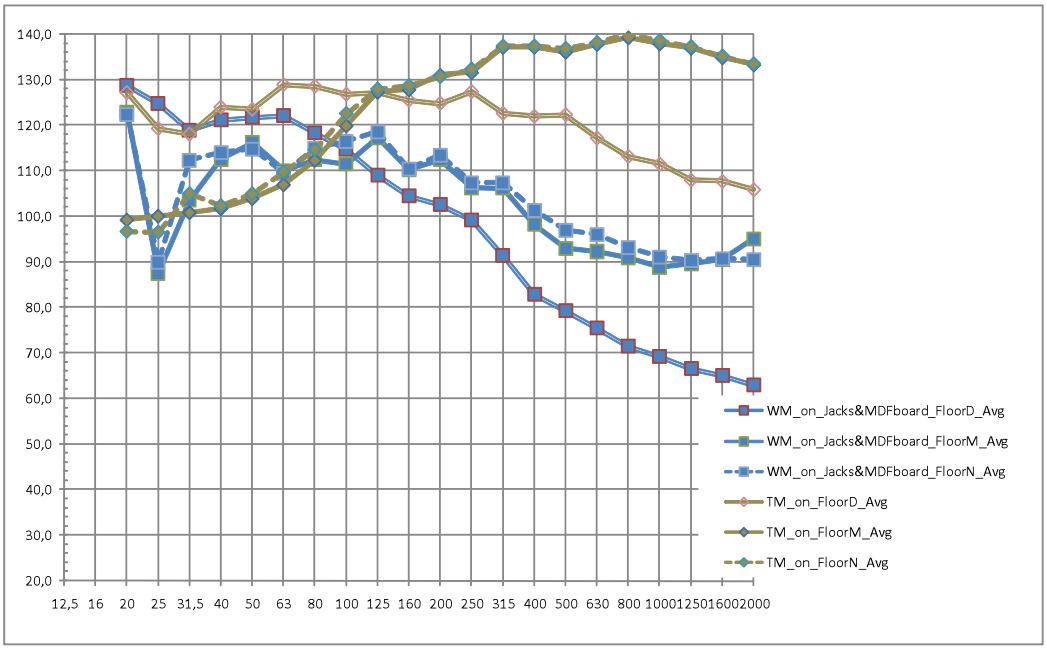


Figure 7c): As for figure 7b, with all vibration levels plotted separately. The washing machine produces significantly higher vibration levels at low frequencies than the tapping machine (except for floor D).

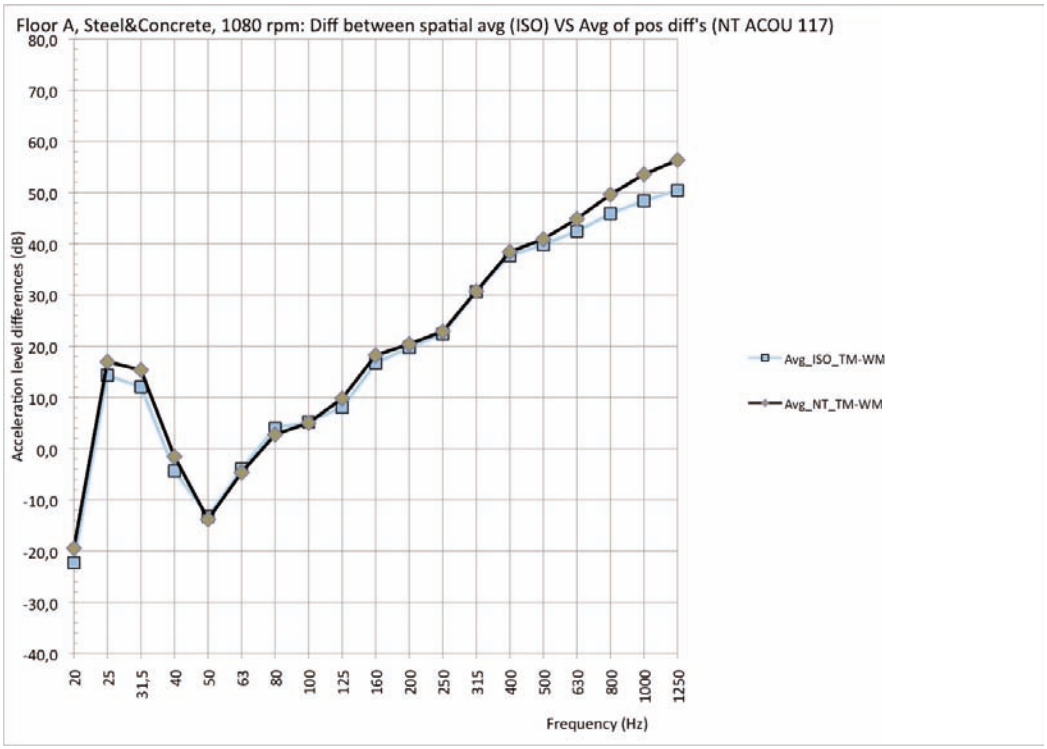


Figure 8:Two types of averaging of the vibration level differences between the tapping machine and the test object, using the steel&concrete base, put on the floor A and running at 1080 rpm. 3 source positions and 4 accelerometer positions. (ISO_TM-WM), the logarithm-average of 12 source and all receiver positions is taken for each source, then their difference is computed. (NT_TM-WM), the difference in level is registred by each accelerometer and source position, then the aritmethic average of 12 differences is computed.

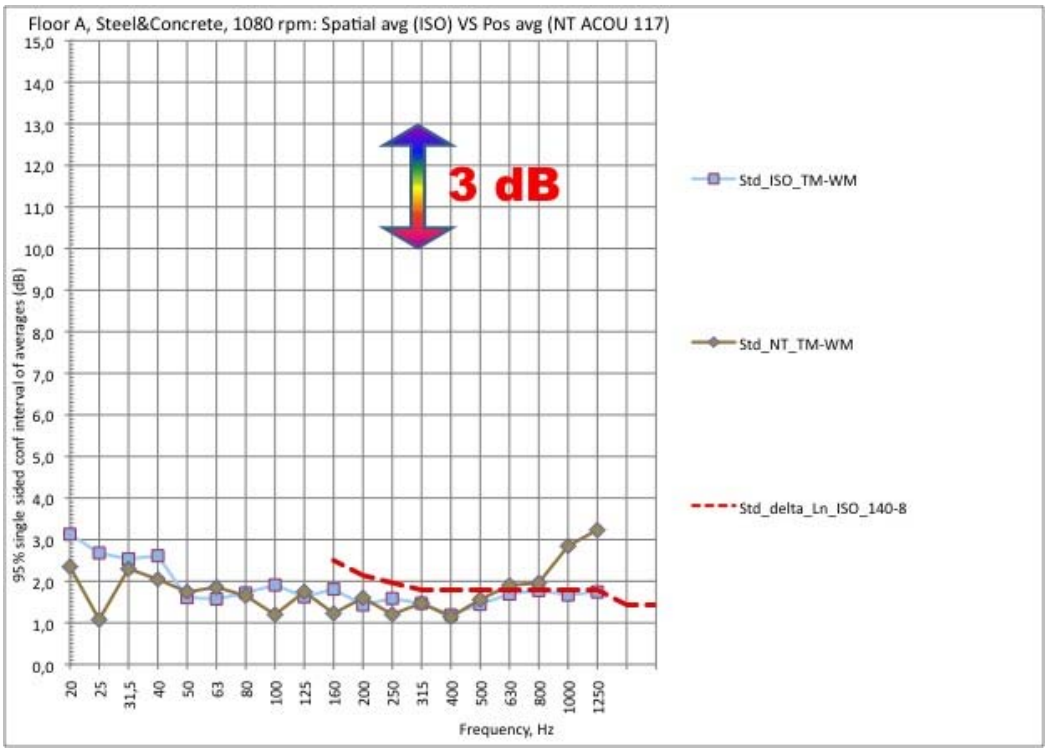


Figure 9: The standard deviation of the ISO-type of average (Std_ISO_TM-WM) and the NT-type of average (Std_NT_TM-WM). For comparison, the expected standard deviation of impact sound reduction of floorings according to ISO 140-8 (Std_delta_Ln_ISO_140-8).

Paper III

Uncertainty of measured and calculated sound insulation in buildings - Results of a Round Robin Test

Christian Simmons[a)]

(Received 2006 February 03; revised 2006 August 09; accepted 2006 August 09)

An inter-laboratory comparison has been made *in situ* with the participation of 8 laboratories. The operators measured airborne and impact sound insulation of 7 partitions according to the ISO 140 standards and some additional guidelines. Variations of sound insulation, and their components, have been analyzed. In addition, field measurements of sound insulation in 40 building cases were compared to calculations according to EN 12354 (-1, -2). Safety margins for predictions of 3 dB are recommended for calculation of heavy building partitions, with respect to an estimated risk of 5% being disapproved by a sample measurement *in situ*. *© 2007 Institute of Noise Control Engineering.*

Primary subject classification: 72.5; Secondary subject classification: 77

1 INTRODUCTION

Uncertainties of measurement and prediction of the sound insulation in a building put increased expenses on all actors of the building process, because they have to keep safety margins to prescribed requirements. Knowledge of these uncertainties and the appropriate safety margins may therefore be a critical factor for these actors. This paper deals with estimates of both types of uncertainty and some recommendations on suitable safety margins for predictions are given.

Requirements on sound insulation are described in the Swedish sound classification standards SS 25267[1] and SS 25268, on the basis of the ISO 140- and ISO 717 series of standards. New standards for the measurement (ISO 140-14, SS 25267 annex H) and the prediction (by calculation) of sound insulation, EN 12354 (ISO 15712), are now incorporated as alternate means of verification of performance *in situ*. The frequency range of interest was expanded to include low frequencies (50–100 Hz) in 1999. Typical requirements on airborne sound insulation is $R'_w + C_{50\text{–}3150}$ 53–57 dB and impact sound insulation $L'_{nw} + C_{I,50\text{–}2500}$ 56–52 dB. This project was initiated in 2001 to examine how the new methods apply to typical building cases with respect to the new requirements on sound insulation (within the expanded frequency range).

In the first part of this study, an inter-laboratory comparison (round robin) has been made in Mölndal, Sweden with the support from Nordic Innovation Center and the eight laboratories participating. The operators made sound insulation measurements on 7 partitions located in the same building. The airborne sound insulations of these partitions ranged from 23 to 47 dB (which are less than required for dwellings). The operators were instructed to follow the procedures of ISO 140 parts 4, 7 and 14, as well as the guidelines in the informative annex H of the standard SS 25267. The guidelines of this annex give some practical information about how to locate the loudspeaker and the microphones, e.g. in narrow spaces where the instructions of ISO 140-4 annex B are not feasible. The differences of the measured sound insulation and its components (sound pressure level difference, normalized impact sound pressure level, reverberation time, partition area and receiving room volume) are analysed in the first part of this paper.

In the second part of the study, about 40 calculations of sound insulation between rooms in real buildings were made by the author according to EN 12354 (ISO 15712). The calculated values were compared to field measurements obtained from consultants from the Nordic countries. The resulting differences (calculated-measured results) include all kind of variations that may be expected and therefore yield a reliable estimate of the uncertainty that may be expected in practical design work. This estimate of uncertainty could even be expected to be conservative, because several details on the building construction measured were not properly documented (in the consultants reports), and default values had to be chosen with respect to traditional constructions in houses of the same age and style. In the individual case, when all details are known, a more precise calculation could be made. However, there are still several uncertainties to consider, e.g. reproducibility of calculations among several operators. There will

a) Simmons akustik & utveckling ab, Krokslätts Fabriker 1, SE-431 37 Mölndal, SWEDEN; email: info@simmons.se

Table 1—Variation of measured airborne sound reduction index and spectrum adaption terms.

Estimated uncertainties, in decibels, dB:	Standard deviation, 7 (all) cases	90% confidence (1,6*Standard-deviation), 7 (all) cases	Standard deviation 5 regular spaces	90% confidence (1,6*Standard deviation), 5 regular spaces
R'_W	1,0	1,7	0,7	1,1
R'_W+C	1,2	1,9	0,8	1,3
R'_W+C_{tr}	1,3	2,2	0,9	1,5
$R'_W+C_{50-3150}$	1,3	2,1	0,7	1,1
$R'_W+C_{tr,50-3150}$	1,7	2,7	0,8	1,3

always be a difference between calculated and measured sound insulation *in situ*. The task is to characterize the mean deviation (and correct for this) and the random variations, (and to recommend a practical safety margin that can be employed by consultants during design work).

2 RESULTS - DETAILS

A summary of uncertainty of weighted values are given in Tables 1–5.

The main parameters studied are variations about the ensemble average of the sound pressure level difference, impact sound pressure level, reverberation time, partition area and the receiving room volume.

2.1 Airborne Sound Insulation

Results for airborne sound insulation are shown in the Figs. 1 and 2 in third octave bands from 50–3150 Hz, followed by the weighted airborne sound insulation including four spectrum adaptation terms, in decibels (dB):

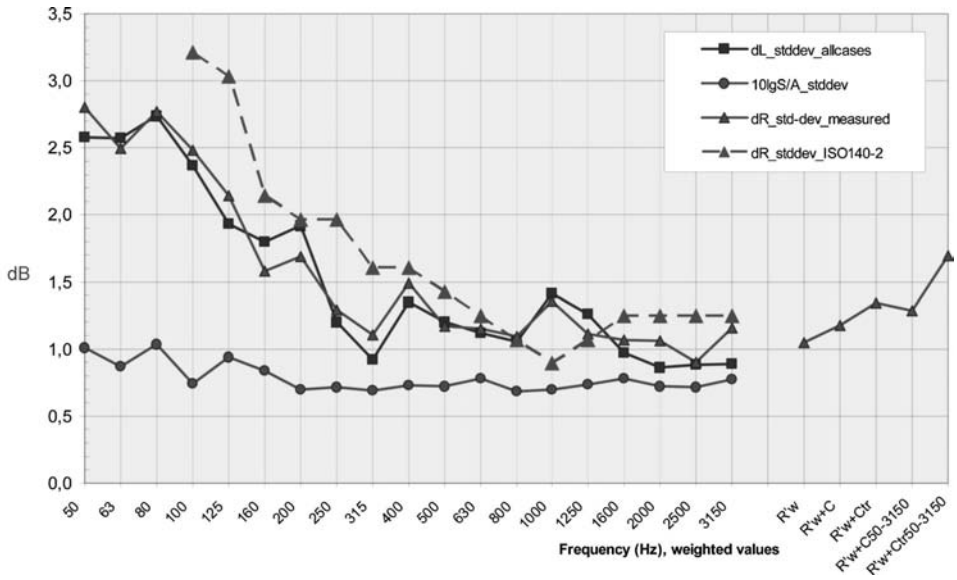


Fig. 1—Standard deviations of the measured values. Legend: "dL-stddev-allcases" denotes standard deviation of sound pressure level differences between the source and receiving room, "10lgS/A-stddev" denotes the standard deviation of the receiving room absorption term $10*\log(S/A)$*, where S denotes the partition area and A the sound absorption area of the receiving room. "dR-std-dev-measured" denotes the standard deviation of the resulting sound reduction index* (R)*, in decibels. All* (7) *measurement cases included.*

Table 2—Variation of measured normalized impact sound pressure level and spectrum adaption terms.

Estimated uncertainties, in decibels, dB:	Standard deviation, 4 cases	90% confidence (1,6*Standard deviation), 4 cases
$L'_{n,W}$	0,7	1,1
$L'_{n,W}+C_I$	0,7	1,2
$L'_{n,W}+C_{I,50-2500}$	0,8	1,3

$$R'_W R'_W + C\ R'_W + C_{tr} R'_W + C_{50-3150} R'_W + C_{tr50-3150}\ \text{(dB)}$$

The overall result, including all (7) cases, for the airborne sound insulation, is shown in Fig. 1. The solid (red) line with triangular marks shows the standard deviation about the ensemble average.[1)] The solid (blue) line with squared marks shows the standard deviation of the sound pressure level difference between the source and receiving rooms. The solid (green) line with circular marks shows the standard deviation of the sound absorption term $10\log(S/A)$, or rather $10\log(ST/0,16V)$. The dashed (red) line with triangular marks shows the standard deviation of sound insulation according to ISO 140-2:1991.

It can be observed from the Fig. 1, that the results obtained in this study resemble the data tabulated in ISO 140-2 and the inter-laboratory comparison study made by Pedersen in 1992.[2] However, there is a noticeable reduction of uncertainty in this study at the low frequencies which may be explained by improvements of the measurement procedures. The main part of the uncertainty is pertinent to the sound pressure level difference ΔL, which depend heavily on the amount of time and spatial averaging. In the guidelines of the informative annex H of the Swedish standard SS 25267, it is stressed that microphone positions must be distributed over the entire measurement space to suppress spatial sampling errors.

In Fig. 2, the standard deviations are plotted as in Fig. 1, but two measurement cases have been considered particularly difficult (i.e. statistical outliers) and removed from the data series. In both cases, the source room SPL average was difficult to determine properly. This is discussed to some detail in the project report.[3]

Figure 2 shows some interesting changes as compared to Fig. 1. The uncertainty of R is still explained mainly by the variations of ΔL, but there is a significant improvement. The uncertainty of the weighted sound insulation R'_W is now only $0,7$ dB. Even more interesting, the uncertainty does not increase when the low frequency spectrum adaptation term $C_{50-3150}$ is added. This conclusion is in accordance with the opinion among some building acoustic consultants in the Nordic countries, who have had a positive experience with the extension of the frequency range from 100–3150 Hz to 50–3150 Hz made to the Swedish building code (BBR) in 1999. Most consultants were by then already using this extended frequency range and supported the changes of code, even though some were very sceptical. It is not clear however, if the consultants also changed the measurement procedure accordingly, so this comparison with practical experience should merely be considered as an indication, not as an evidence. This is discussed to some detail in the project report.[3] In Table 1, the uncertainties of the weighted values are listed.

2.2 Impact Sound

The normalized impact sound pressure levels L_n, in decibels (dB), were determined by 4 of the operators in four cases. The operators were not the same in all building cases. The overall variation of results (standard deviation) are demonstrated by Figs. 3 and 4, where comparisons with the standard deviation of reproducibility taken from ISO 140-2 are included. In Table 2, the uncertainties of the weighted values are listed.

2.3 Partition Area and Receiving Room Volume

One interesting variable that influences the sound insulation is the absorption term, which is derived from the area S of the common partition, the volume V of the receiving room and its reverberation time T. From the measurements, the sample standard deviation of the factor $10\log(ST/0,16V)$ was determined to $0,6$–$0,8$ dB, including the variation of reverberation time T. A brief survey was made among the operators on the choice of S and V for 5 additional (schematic) cases (with a fixed value of T). The cases comprised dwellings with open plan constructions, or regular spaces with several wardrobes or a toilet room covering parts of the partition and receiving room. The sample standard deviation was then $0,7$ dB (one outlier was removed from the set of data, the deviation was $1,2$ dB including this special case). This indicates, that it could be worthwhile to make an attempt to improve the instructions of the measurement standard to make the choice of S and V less ambiguous. Another strategy would be to express sound insulation requirements as $D_{nT,W}$ instead of R'_W. Then, the choice of S and V does not have any influence on the result. A compromise, adopted in SS 25267, was to restrict the ratio V/S

[1)] All standard deviations in the report are calculated as the sample standard deviation of the measured values, in decibels[1].

Table 3—Reverberation times of a conference room, obtained by a detailed measurement. 40 reverberation decays were sampled (in all) using 20 microphone positions and 4 loudspeaker positions. Frequency in third octave bands (Hz). "T-av" denotes aritmethic average values, "T-sd" denotes sample standard deviation of reverberation times, in seconds (s).

Freq.	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250–3150
T-av	1,16	0,66	0,63	0,55	0,65	0,64	0,78	0,85	0,97	0,98	1,03	0,98	1,03	1,05	1,0
T-sd	0,31	0,27	0,21	0,17	0,24	0,18	0,17	0,16	0,27	0,11	0,22	0,18	0,10	0,13	≤0,09

Table 4—Comparison between measured and calculated sound insulation.

Difference calculated-measured insulation, in decibels:	R'_W	$R'_W+C_{50-3150}$	$L'_{n,W}$	$L'_{n,W}+C_{I,50-2500}$
…between the averages	−0,17	0,42	1,87	1,91
…standard deviation	2,3	1,6	4,4	2,9
…90%-confidence limits (5% risk of non-conform.)	**3,5**	**3,0**	**5,1**	**2,7**
Number of comparisons	*26*	*36*	*30*	*43*
Measured average of sound insulation	*59,4*	*57,6*	*54,1*	*51,3*

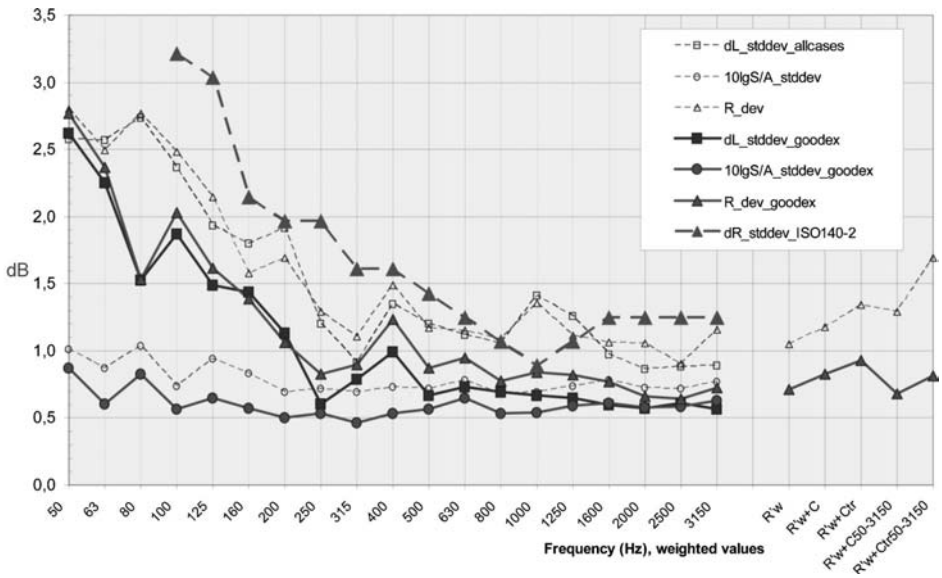


Fig. 2—Standard deviation of sound pressure level differences, the receiving room absorption term and the resulting sound reduction index, in decibels. Calculated for 5 "well defined rooms". The dashed thin lines replicate values from figure 1. The solid lines show the same quantities as in figure 1, but the results are based on data of 5 well defined rooms.

$\geq 3,1$ meters in which case R'_W equals $D_{nT,W}$. For impact sound, $L'_{n,W}$ is equal to $L'_{nT,W}$ when $V \geq 31$ m^3, and this limitation was also added to SS 25267.

3 ESTIMATION OF UNCERTAINTY IN THE INDIVIDUAL CASE FROM SOUND FIELD VARIATIONS

In an attempt to apply the ISO GUM procedure,[4] some data were collected by the author to make an uncertainty budget and compare this to the variation of data between the operators. Some detailed measurements were made in the building case A, between an office and a small conference room. The sound pressure levels were measured at 38 fixed positions in the source room (L_s) (office), 0,3 m apart, 0,5 m and 1,5 m above the floor, >0,5 m from the walls and ceiling. The same grid of microphone positions was used with a second loudspeaker position, thus a total of 76 SPL were measured in the source room. The increase of SPL close to the loudspeaker was observed and positions closer than 1,5 m from the omnidirectional loudspeaker were excluded. In the conference room, the grid of measurement positions covered 2 $\times$22 positions at 0,7 m distance from each other, 0,5 m and 1,5 m above the floor, >0,5 m from the walls and ceiling (L_m). The same 2 loudspeaker positions were then used in the source room.

The reverberation time was measured in the receiving room using 2 loudspeaker positions, 5+5 fixed microphone positions (distributed over the entire space). The measurement was repeated, thus 20 different microphone positions were used. Two decays were recorded in each position. Each decay was inspected visually on-screen. Decays with a correlation to the straight line less than about 0,96 were rejected or the on-set/off-set points were adjusted to make the decay regression line fit the early part (−5,−20 dB) of the decay curve. At low frequencies, erroneous regression lines were common and the measurements had to be repeated several times. The reverberation times (average and standard deviation) obtained in the conference room are given in Table 3.

From the guidelines in ISO 140-14 and the reverberation times in Table 3, there is no reason to believe that there should be excessive spatial variations of the sound pressure level in the receiving room. In the source room, there are no sound absorbing tiles or furniture, but the shape of ceiling and diffusive effects of a large table and some bookshelves were judged to be sufficient to make the sound pressure diffused. In Fig. 5, the measured standard deviation of L_s and L_m (solid lines) were then compared to the guidelines of ISO 140-14 figure A.1 (reproduced in Fig. 5 with dashed lines), for the purpose of checking the diffusivity of the measurement rooms.

It appears from the Fig. 5, that the measurement

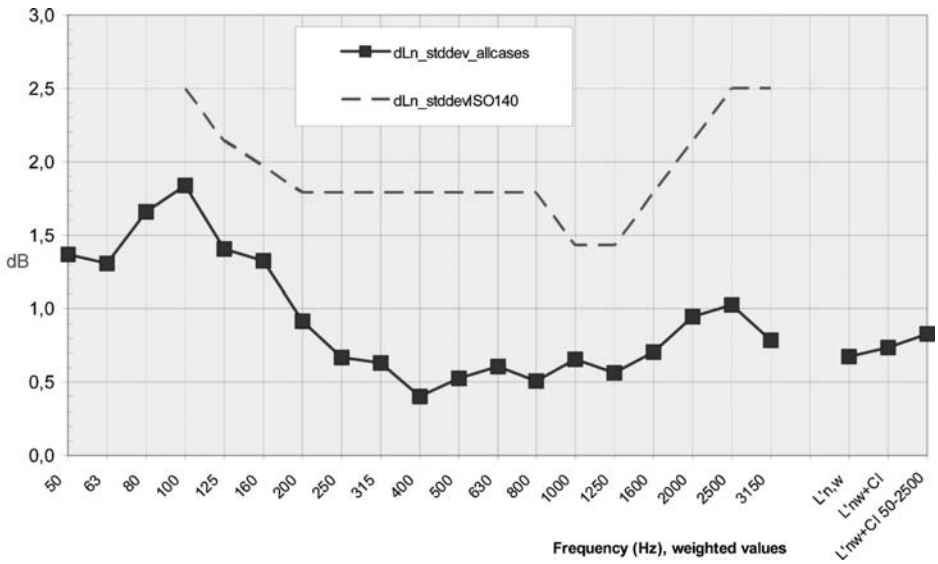


Fig. 3—Standard deviation of normalized impact sound pressure levels, 4 measurement cases (dLn-stddev-allcases), in decibels. The standard deviation of reproducibility of ISO 140-2 is included for comparison (dashed line, dL-stddevISO140).

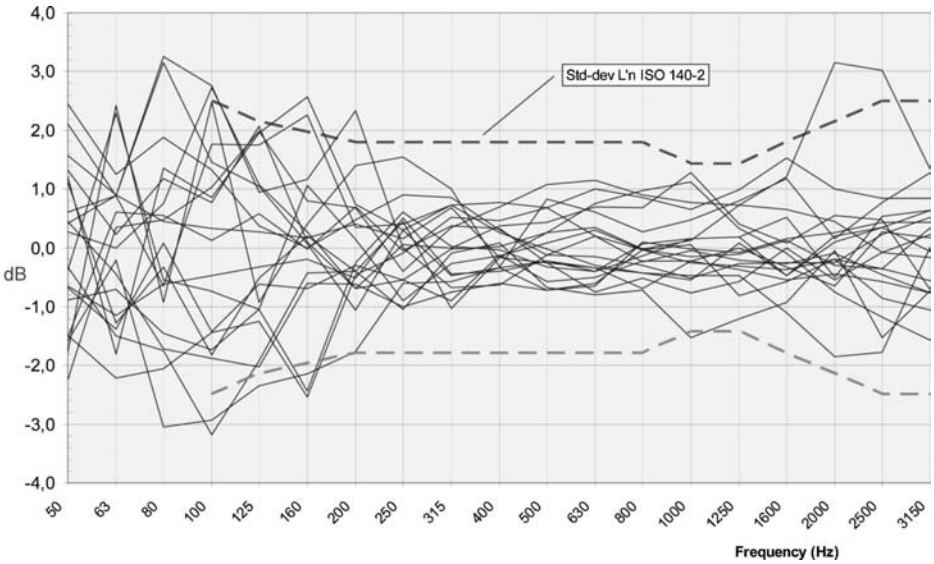


Fig. 4—Illustration of the variation of normalized impact sound pressure levels, all cases, with the standard deviation according to ISO 140-2 plotted for comparison (dashed lines), in decibels.

spaces in case A (both the office and conference room) are less diffuse than anticipated from the reverberation times. This may be explained by the irregular shapes of both spaces and the uneven distribution of sound absorbing tiles in the receiving room.

Figure 6 shows a comparison, where the uncertainty of case A is estimated from the measured standard deviation of the L_s, L_m and T. The variation of the ratio S/V was estimated by the author from some plausible variations of geometrical dimensions, as seen from the source room or the receiving room. A standard deviation of 0,5 dB is added to the uncertainty budget to take variations in instrumentation sensitivity into account. This value (0,5 dB) has been found by comparison of calibration data for sound analyzers at SP, Sweden.

The agreement is satisfying at low frequencies, but at high frequencies the estimated uncertainty exceeds the actual uncertainty (as determined by the operators). The reasons for this deviation may be that the operators used a single channel analyzer or dual channel analyzer with matched microphones, thus errors in sensitivity are cancelled. If the 0,5 dB is removed from the estimated uncertainty, the agreement is improved at high frequencies. Additional analysis of the data will be proposed to the ISO TC 43/SC 2/WG 18/AHG 2.

4 CALCULATIONS - CONSIDERATION OF INPUT DATA

When a theoretical model of a building is established according to EN 12354 (ISO 15712), several decisions must be taken by the operator.

- Appropriate input data for each building element that enclose the transmission rooms must be chosen.
- The operator has to define the size of partitions and room dimensions. The size of the model may differ from the actual physical dimensions, particularly where the geometry of the building is complicated, e.g. staggered rooms and open-plan spaces.
- The operator has to define the junctions between the building elements.
- The actual performance of elements in the building depends on to which elements it is connected, and the quality of workmanship (air leakages, structural sound bridges etc.) Another important issue is the choice of loss factor, that relates to the structural vibration energy transmission through external building elements (i.e., elements that are connected firmly to the partition and flanking structure and therefore extract energy from the "system", but do not increase the flanking transmission to the receiving room). This loss factor is particularly im-

Table 5—Recommended safety margins for calculations of heavy building constructions.

Practical safety margin to a requirement, in decibels	R'_W	$R'_W+C_{50-3150}$	$L'_{n,W}$	$L'_{n,W}+C_{I,50-2500}$
in an individual case, as verified by one sample measurement:	2	3	2	3
as an average of measurements, allowing 2 dB deviation (if the average value conforms with the requirement)	0	1	0	1

portant for heavy building systems. Large concrete slabs, with room partitions built by light weight plasterboard walls, will give substantially higher sound insulation vertically than buildings with heavy partition walls. This is sometimes referred to as the "area factor" and it is treated in EN 12354.

- One may assume that calculation results may vary depending on the operators experience and which building element data in the database is considered most appropriate to include in a model of the real building construction.
- When comparisons are made with respect to the conformance to field measurements, measurement uncertainty has to be taken into account.

There was a need to compare measurements and calculations of real buildings, to see whether there are systematic or random errors that need to be taken into

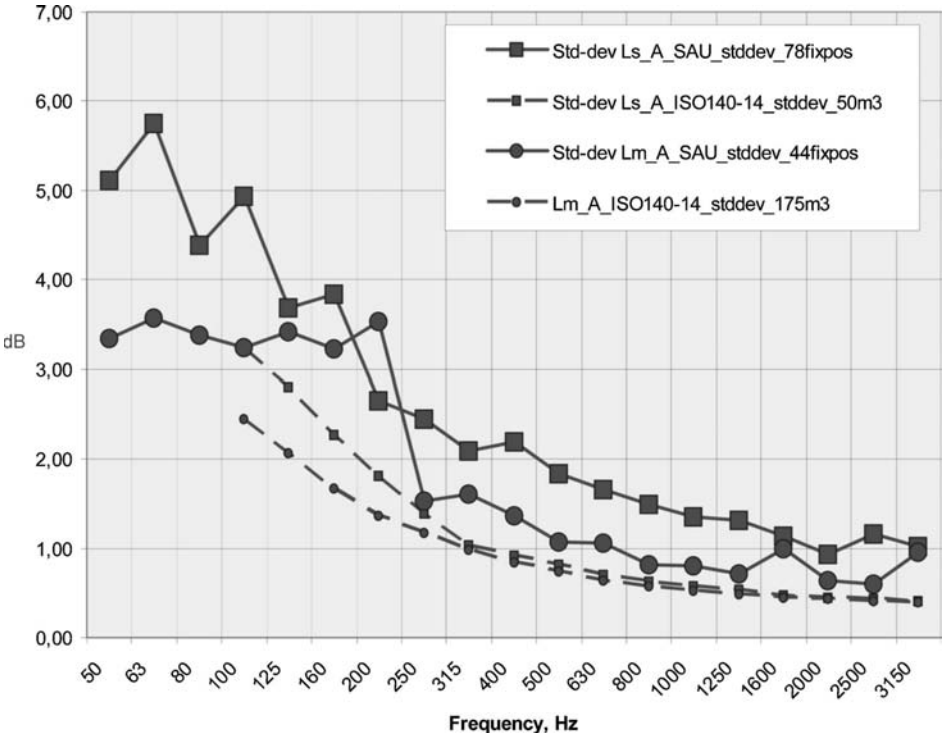


Fig. 5—Comparison of measured standard deviation of sound pressure levels (solid lines) to values estimated from the measured reverberation times according to ISO 140-14 figure A.1 (dashed lines), in decibels. Legend: "Std-devLs-A…", lines with box markers, refer to the source room (an office) and "Std-devLm-A…", lines with circle markers, refer to the receiving room (conference room).

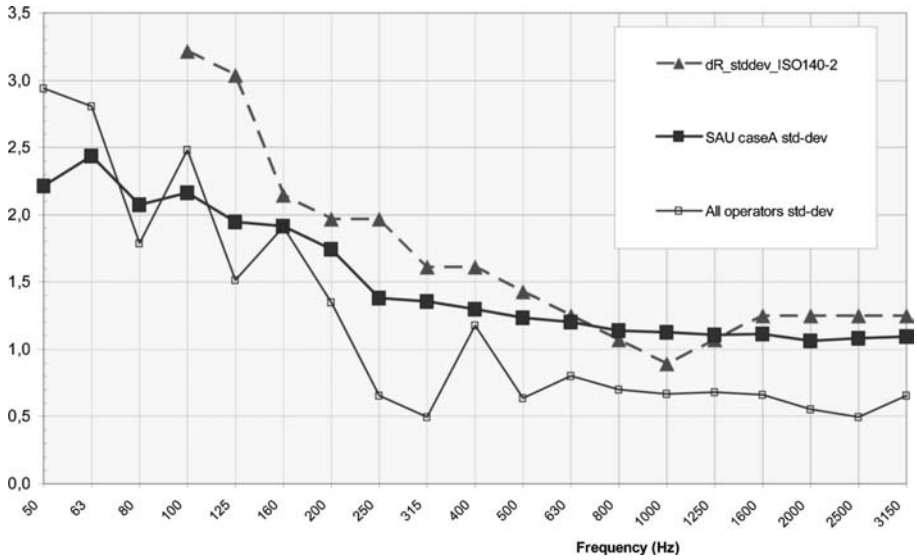


Fig. 6—Estimated standard deviation of uncertainty of the sound reduction index (“SAUcaseA std-dev”) as compared to standard deviation values obtained by 8 operators in the same rooms (“Alloperators std-dev”), in decibels. Values from ISO 140-2 added for comparison (dashed lines).

account. The sound insulations in a variety of building cases (mainly residential buildings) have been analysed by the author, using the BASTIAN software and a propriety database of building elements.[5] The comparison between measured and calculated sound insulation, in the Table 4, refers to vertical sound transmission through concrete slabs with different floorings. The number of comparions are given for each case.

The measured building cases were not properly documented with respect to all building products and construction joints used in the respective building. When the calculations were made, data for constructions typical for the age and type of building were used when no other information was available. Naturally, such assumptions increase uncertainty of the calculations. In spite of these uncertainties, the Table 4 shows that the 90% confidence limits agree reasonably well with a common experience, that a 3 dB margin is sufficient for most practical applications. The risk of a field measurement (performed according to all relevant standards) being non-conformant to the requirement is then less than 5%. This confidence limit corresponds to a coverage factor of $k=1,6$, assuming the random variations being normal distributed (being justified by the fact that several independent variables influence the final result) and the influence of systematic errors being negligible. If well documented building products are used, and the quality of workmanship is high, it should be possible to reduce the margins, according to the recommendation in Table 5.

In order to estimate the influence of the operator (reproducibility of calculations according to EN 12354), 4 of 8 the operators contributed sound insulation values of 7 hypothetical (rather complicated) building constructions, calculated according to EN 12354 (ISO 15712) parts 1 and 2. Two of these operators were not experienced with the standardised calculation procedures. The standard deviation of the calculated weighted airborne and impact sound insulations are given in Table 6. The results of this simple comparison may possibly be considered as examples of uncertainty that may occur in real consultancy work, but the low number of experienced operators (2) who delivered

Table 6—Variation of calculated sound insulation, 4 operators (of which 2 experienced with EN 12354), 7 building cases.

Standard deviation, 4 operators, all cases, in decibels			
R'_W	$R'_W+C_{50-3150}$	$L'_{n,W}$	$L'_{n,W}+C_{I,50-2500}$
3,0	3,0	2,6	2,3
Standard deviation, 4 operators, 1 complicated case (diagonal measurement) excluded			
R'_W	$R'_W+C_{50-3150}$	$L'_{n,W}$	$L'_{n,W}+C_{I,50-2500}$
2,6	2,6	1,8	1,4

results, and the complexity of the calculation examples, prevent an interpretation of the results to obtain reliable estimates of the uncertainty of the calculation method.

No comparison has been made in this project of data for light weight slabs, but the practical experience is that the margin must be increased compared to the uncertainty values given above. This depends on the type of product and the quality of workmanship. Some indications are given by Pedersen.[6]

5 SUMMARY OF RESULTS

The uncertainties calculated from the comparisons described above are given in Tables 1 and 2. The project report[2] contains some advice on possible improvements of the measurement procedure, a detailed description of the study and all results.

From the measurements, the sample standard deviation of the weighted airborne and impact sound insulations and the spectrum adaptation terms R'_W (C;C50-3150) and $L'_{n,W}+C_{I,50-2500}$ are presented in Tables 2 and 3.

To estimate the uncertainty of a calculated sound insulation to a sample measured value, about 40 field measurements were collected from consultants in the Nordic countries and analyzed by the author. Estimates of the sound insulation between the rooms were made with calculations according to EN 12354 (ISO 15712). All measurements had been made vertically in buildings with concrete slab floors, with various floorings, where a mix of heavy and light walls defined the measurement spaces. The resulting differences between calculated and measured values yield a more reliable estimate of the practical uncertainty that may be expected in practical planning work, because all kind of uncertainties are included in the comparison.

The software used for the comparison was BASTIAN version 2.1 and the input data for concrete slabs, floorings and walls were taken from the Nordic database for this software, used by several consultants in the Nordic countries. The number of comparisons is given for each type of weighted value in Table 5.

The values of Table 5 correspond to practical experience and approximately to the results of a previous Nordtest study by Pedersen,[2] except for $L'_{n,W}$ which is higher than expected, but reasons for this has not been examined further.

From the results presented, the safety margins of Table 5 are recommended for practical planning work, applicable when sound data of building elements have been tested and documented properly, and the quality of workmanship is high. Under these conditions, the uncertainty may be assumed less than given in Table 4. The margin does not guarantee that non-conformance with requirements may never occur, it must be expected that measured sound insulation may occasionally be less satisfactory than predicted, by say 1–2 dB, if the safety margins given in Table 5 are applied during the planning process.

The measurement uncertainty may be reduced to some extent by a careful measurement work and an extended averaging procedure. The uncertainty of calculations of the performance in a building with specified products may be reduced by a continuous comparison between predicted and measured sound insulation. Input data for the calculations may initially be taken from laboratory values or theoretical calculations, and adjusted after some time if empirical experience proves there are systematic differences that need to be compensated for. The manufacturers should take on the responsibility for maintenance of their data, but all actors of the building industry could contribute, with an open mind to exchange of experience.

6 REFERENCES

1. SS 25267 *Acoustics - Sound classification of spaces in buildings - Dwellings*. SIS standardization body, www.sis.se. In Swedish (a translation to English is under preparation). Stockholm (2004).
2. D. B. Pedersen, *Nordic Intercomparison Programme in the field of Acoustics. Measurement: Field measurements of airborne sound insulation*. Delta Akustik & Vibration, Nordtest project report No 1023-92. In English. www.delta.dk. Aarhus (1998).
3. C. Simmons, *Final report of project 04030. Reproducibility of measurements with ISO 140 and calculations with EN 12354* Nordisk InnovationsCenter (formerly Nordtest, www.nordicinnovation.net). In English. Oslo (2005).
4. *Guide to the expression of uncertainty in measurements*, International Standard ISO 199, International Organization for Standardization, Geneva Switzerland, (1994).
5. C. Simmons, *Reliable building element sound insulation data for EN 12354 calculations facilitates analysis of Swedish dwelling houses*. Inter-noise proceedings, Prague (2004).
6. D. B. Pedersen, Delta Akustik & Vibration. Nordic basis of calculation of sound insulation in buildings. Report Nordtest project 1346-97. In English. www.delta.dk. Aarhus (1999).

Paper IV

ACUSTICA · acta acustica
Vol. 85 (1999) 88 – 100

Measurement of Sound Pressure Levels at Low Frequencies in Rooms. Comparison of Available Methods and Standards with Respect to Microphone Positions

Christian Simmons
SP Swedish National Testing and Research Institute, Acoustics, Post Box 857, SE - 501 15 Borås, Sweden

Summary
Within a Nordtest project, a comparison has been made of all methods found in a literature survey (24 methods) for the determination of the sound pressure level in a room. New principles for the location of the measurement microphone were tested. The existing general purpose methods intended mainly for the measurement of A-weighted sound pressure levels show an unacceptable scatter between measurement results when the sound is dominated by low frequency sound or if the sound is measured in octave or third octave bands. The reproducibility (i.e. the statistical uncertainty in the determination of the sound pressure level), is in the order of 15 dB at low frequencies. The methods also underestimate the C-weighted, octave and third octave band values below 200 Hz, which is an interesting finding in the context of the discussion of whether the A-weighting is too accentuated at low frequencies and thus would underestimate the subjective annoyance of noise dominated by low frequency sound. At frequencies higher than the 250 Hz octave band, most of the methods work satisfactorily except for some specialized corner methods. Arithmetic averaging increases the uncertainty at low frequencies. Some new methods based on moving microphones with large radii, or many fixed distributed positions, or the use of a specified corner location all perform satisfactory, both with respect to deviation from the true room average (bias error) and to scatter (reproducibility). The project group outlined a new method, based on the concept of scanning the corners of the room for the corner with the highest C-weighted level (as in the present Swedish standard SS025263), and including this measurement position in the spatial average. Two more positions are chosen in the reverberant field. It seems that this concept reduces the measurement effort and the scatter, it also improves the correlation to the room average. This new method was tested in an Inter-Nordic Round Robin comparison with 5 laboratories, where very good reproducibility was achieved. The bias error (defined as the deviation of the measurement result from the average of 6 room positions measured in the central part of the room) was very low. The new principles for the location of the measurement microphone have been proposed to CEN TC 126/WG 1 which is working on new EN standards that will replace the current national standards/methods within the EU.

PACS no. 43.

1. Introduction

It is a common opinion that low frequency noise from i.e. technical installations may cause annoyance to the habitants even if the A-weighted sound pressure level is well below the limiting value (typically 30 dB). Therefore, some building codes and sound quality classification standards contain additional requirements on the maximal sound pressure levels in dwellings, offices etc. at low frequencies (in octave bands or third octave bands). However, low frequency noise has often been measured with the same methods that were intended for the measurements of broad band noise since there has been a lack of acceptable methods dedicated to the measurements at low frequencies. The resulting measurement uncertainty is unacceptable because of large variations of sound pressure levels at low frequencies within the room.

There are at least three different aspects or requirements on how to position the microphones within an enclosure for the purpose of assessing subjective annoyance. These requirements are often not mutually compatible and a best choice must be agreed on with respect to

- ensuring reproducible measurements (low uncertainty, low bias error),
- giving results that are representative to the habitants or users of the room (assess the annoyance),
- being easy to understand, quick and easy to perform correctly.

An efficient means to meet the first requirement is to make measurements in many points in the room, and average the results (e.g. as in ISO 140). This is, however, an expensive and impractical solution. To assess the subjective annoyance of the actual sound field in the room (second requirement), the maximum sound pressure level (SPL) in the room may be preferred. This however leads to decreased reproducibility since small changes in e.g. the position of the microphone, temperature, furniture, doors, windows etc. influence the results at a specified location in the room (apart from time variations of the noise that reduces reproducibility furthermore). A quick-and-easy-to-use method (third requirement) should be written in a way that is easy to understand (unambiguous) and which requires a minimum of advanced equipment. The latter requirement speaks against the use of many parallel microphones, multiplexers, advanced multispectrum sound analyzers etc. The project group outlined a new method, based on the concept of scanning the corners of the room for the highest C-weighted level as in the present Swedish standard SS025263, and including this measurement in the spatial average. The performance of this method is supported by other researchers and consultants who have made their own reproducibility tests in rooms with this type of method as well as with other methods [1, 2].

This study was only concerned with continuos noise. The limitation was justified by the assumption that variation of

Received 5 December 1997,
accepted 28 February 1998.

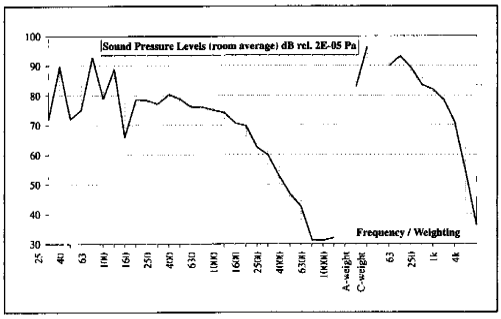


Figure 1. Pseudorandom noise with pure tones at 31, 63 and 94 Hz in the spectrum. The left part of the x-scale shows third-octave band values, followed by A- and C-weighted and octave band values.

sounds does not make the spatial variation on the room average more complicated than continuos noise. In the limit, impulsive sounds give a peak level that depends only on the distance between the source and the microphone, irrespective of the reverberation of the room. However, the influence of the time variations on the room average remains to be investigated.

2. Comparison of existing methods by simulations

The sound pressure levels were first measured in 10 different rooms at a great number of positions equally spaced throughout the room. Some analyses were made on a simulated reverberation chamber with single room modes as well, but the results were not included in the averages presented below. Each of the known 24 standards/methods was then tested in each room by means of its specific instructions on where to put the microphones. A "measurement" with a method was simulated by means of a random choice of measured data at acceptable positions. The average deviation from the true room average (calculated from all measurement positions) and the standard deviation in each room were calculated and averaged over all rooms to estimate the overall systematic difference (to the room average) and the reproducibility of the method. This procedure was repeated for each of the 24 methods available.

2.1. Measurements of sound fields in rooms

2.1.1. Measurements

The sound pressure levels of continuos noise (of different types) were measured in 10 different rooms in a great number of positions. The data are available for easy download from the Internet (at `http//:www.sp.se/pne/acoustics`). The microphones were placed in a symmetrical grid across the rooms with typically 0.5 m (0.3–1.0 m) spacing 0.5 to 1.5 m above floor. At some special positions, additional heights were used. The closest distance to the walls was 0.2 m except in the corners were the microphone was mounted as close as 0.01 m (two methods use this distance).

2.1.2. Rooms and sound sources

The 10 rooms used are listed in Table I. The choice of rooms was made in order to obtain difficult cases with uneven sound fields, but a few rooms were included as well that were believed to have diffuse sound fields. Both furnished and unfurnished rooms were included.

The noise signals applied to the loudspeakers were approximately pink noise except in the last two room cases where the noise also contained pure tones according to Figure 1. The room data measured only below 1 kHz are taken from a previous study intended for low frequency sound only.

2.1.3. Examples of sound fields in rooms

In the Appendix A of the project report [3], isobar plots and cumulative distributions of percentage of microphone locations as a function of the SPL at 63 Hz are plotted for all rooms. The 63 Hz third- octave band values was presented because it shows a larger scatter in the analyses (on the average) than the neighboring frequency bands.

2.2. Simulations of measurement methods

2.2.1. Approach

Each standard/method was tested by implementing the specific instructions on where to put the microphones (stated minimum and maximum distances to the walls and floor, minimum distance between the positions and minimum distance to the source, see Table II). A "measurement" with a method was then simulated by randomly selecting measured data at acceptable positions. Typically 50–150 combinations were found (for the distributed methods). All combinations were used to calculate the arithmetic average and standard deviation to estimate the systematic (bias) error (as compared to the average of all room positions) and the reproducibility of the method. This procedure was repeated for each of the 24 methods available. The results are given in Annex B of the project report [3]. Finally, an average of the results for each method was taken for the 10 rooms investigated. The result graphs are given in Appendix C of the project report [3]. The way the results from each room was averaged means that the results from each room are weighted equally in the final average. This was thought to be the most relevant choice. Another choice discussed was to base the averaging on the number of "independent" combinations found in each room, this would give increased weight to the results from the larger rooms. This choice was rejected later because it was not possible to assume that the combinations from one room could be considered "independent". The acoustic properties of each room may bias all calculated combinations in an unpredictable way. Furthermore, the relevance of results from each type of room was considered equally important, the proposed method must work equally well in all common types of room.

Table I. Rooms used for simulations.

Room	Dim	Furniture	Absorption	Sound Path	Source	Frequency
Living room with two entrances (to other rooms)	4 x 5 x 2.60 m	Furnished	T60<0.5 s All light-weight constructions, windows on two facades	Indirect through timber joist floor	Loudspeaker, Pseudorandom pink noise	< 1 kHz
Large Class Room	7 x 10 x 3.50 m	Furnished with hard chairs & pulpits	T60<1.0 s. Absorbing ceiling. Concrete floor, light-weight walls, windows on one facade	Indirect through light wall	Loudspeaker, Pseudorandom pink noise	< 1 kHz
Children's Day Room (Day-center)	6 x 5.5 x 2.60 m	Furnished with soft furniture, diffusing shelves etc.	T60<0.5 s. Light-weight floor, light-weight walls/ceiling, windows on one facade	Direct through wide opening to small side-space	Loudspeaker, Pseudorandom pink noise	25 Hz–10 kHz
Children's Play Room (Day-center)	6 x 6.1 x 3 m	Not furnished, smooth surfa-ces. Sloping ceiling	T60<0.8 s. Light-weight floor, light-weight walls/ceiling, windows on one facade	Direct through wide opening to small side-space	Loudspeaker, Pseudorandom pink noise	25 Hz–10 kHz
Conference Room	6 x 5.5 x 3.40 m	Furnished with 1 large central table & chairs	T60<0.8 s. Concrete floor and facade, light-weight inner walls/ ceiling, few small windows in part of facade	Direct through opening in ceiling	Fan outlet, no silencer	< 1 kHz
Impact Sound Laboratory, absorbers added	5,2 x 6 x 3,1 m	Diffusing items	T60<1.2 s, Concrete floor, walls/ceiling. Plaster wall one side	Indirect through light wall	Loudspeaker, Pseudorandom pink noise	< 1 kHz
Vibration Laboratory (with absorbers)	5 x 5 x 3,50 m	Diffusers on walls	T60 < 1s, Concrete floor, light-weight walls and ceiling	Direct, with the fan at the ceiling	B&K Reference Sound Source	< 1 kHz
Small Reverberation Chamber. Added absorbers + diffusers	4,5 x 3,1 x 3,75 m	Diffusers and absorbers on walls	T60 < 0.8s, All concrete surfaces	At corner 3,8x2,4x2,20 m facing corner	Loudspeaker, Pseudorandom pink noise	25 Hz–10 kHz
Small Reverberation Chamber. Added absorbers	4,5 x 3,1 x 3,75 m	Diffusers and absorbers on walls	T60 < 0.8s, All concrete surfaces	At corner 3,8x2,4x2,20 m facing corner	Loudspeaker, Pseudorandom noise with tones (see Fig. 1)	25 Hz–10 kHz
Small Reverberation Chamber. (Small LF-absorbers)	4,5 x 3,1 x 3,75 m	Diffusers and absorbers on walls	T60 < 0.8s, All concrete surfaces	At corner 3,8x2,4x2,20 m facing corner	Loudspeaker, Pseudorandom noise with tones (see Fig.1)	25 Hz–10 kHz

2.2.2. Methods

Table II below summarizes the requirements on microphone positions as interpreted from the method stated in the first column of the table. The rules of most methods mentioned had to be slightly modified according to the corresponding notes below the table. These approximations were made in order to make the data measured in a fixed grid applicable.

When evaluating the methods from the same measured set of data, the first step is to omit positions that are excluded according to the rules of the method, e.g. positions too close to the walls. Some of the methods require a few special

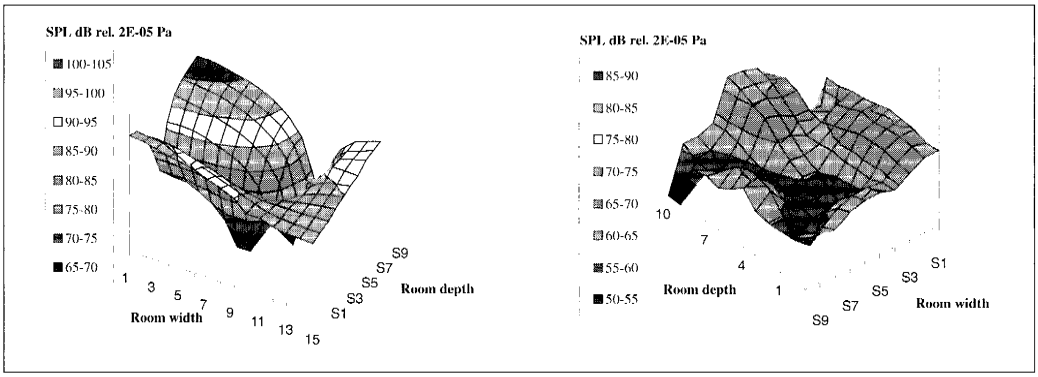


Figure 2. The isobar plots at 63 Hz in a small reverberation room (left) and a day-room at a children's day-center (right) illustrate that the sound field may be quite uneven and unsymmetrical. Note: In the right figure 2 points at upper left and 2 points upper right are not measured which unfortunately is displayed as zero values. 85 and 72% respectively of all positions in the these rooms have sound pressure levels 6 dB below the maximum value or less at 63 Hz. The figures illustrate that is vital to make an average and to choose the right corner in the "corner-type" of methods. Measuring in the central region of the room only gives low levels compared to the corners and the room average.

positions. Most methods allow for many combinations of positions. The following procedure was used.

1. The positions used in each average (the "members") and the averaged equivalent sound pressure levels in frequency bands are stored in a column on a spread-sheet for each one of the methods. Each column correspond to a "measured" result according to the method. A separate column finally calculates the mean value and the standard deviation (based on unknown size of population) of the results.
2. The first member of a combination (position) is chosen as a random number (except in method SS..63_Cfix where a fixed corner position selected).
3. The second member is chosen as a random number.
4. The conditions on distances and logical "Not Measured" are verified (with respect to empty data fields, distances too cloose to the room surfaces or previous positions, special requirements on unequal distances etc.) If any of these tested conditions is negative, the chosen position is not acceptable. Thus, repeat step 3. If the the tested conditions are positive, continue with step 5.
5. The third position is chosen and evaluated as in step 2–4. All requirements on distances must be fulfilled.
6. The set of 3 positions are averaged on an energetic or arithmetic basis (see Table II) and stored according to clause 1 including the identification (ID) of the positions.
7. If more positions are included in the method, continue as in items 2–6.
8. Continue the process until all positions have been used or until the mean value and standard deviation do not alter significantly (<0.3 dB). This was checked from time to time by repeating the calculations.

The condition "Distributed" is implemented by forcing the condition that neither the x nor the y values may be equal among the members of the average. "Not on symm. line" is implemented by excluding $x/2$ and $y/2$ positions. "Room Center or Close to room center" means within the range $x/4 - 3x/4$, $y/4 - 3y/4$. "Unequal dist. to room surfaces" means that d (see equation (2) below) may not be equal among the members. The distance r between two points (x, y, z) and (a, b, c) in a space is

$$r = \sqrt{(x-a)^2 + (y-b)^2 + (z-c)^2}. \tag{1}$$

The distance d between a point in a rectangular space and the room surface is

$$d = \min\Big\{(x - x_{\min}), (x_{\max} - x) \tag{2}$$

$$\cdot\,(y - y_{\min}), (y_{\max} - y) \tag{3}$$

$$\cdot\,(z - z_{\min}), (z_{\max} - z)\Big\}.$$

2.3. Results

2.3.1. Results - overview

The Figure 3 below shows an overview of the simulation results for all the 24 methods according to 2.2. The ISO 140-3 method for the standardised frequency interval 100- 3150 Hz (see Table II) is used in all graphs below as a reference method (fat solid crossed lines). The displayed results for the A- and C-weighted sound pressure levels are only valid for the measurement spectra used in this study, which where chosen in a random way according to 2.1. Depending on the actual spectrum in a specific case, the A- and C-weighted values may change because they result from the weighted sums of the third octave or octave band values.

Note: The overview of Figure 3 is too complex to enable reading of details but is included merely to illustrate the large scatter and poor measurement precision at low frequencies (LF). The mean standard deviation of the method ÖNORM_LF was not possible to calculate, the amount of data is not sufficient since it is only possible to simulate two measurements in each room, each taken as the average of

Table II. A. List of References / Methods simulated using the data according to Appendix A in [3].
Remarks (Parts A and B): "x": Not stated in the method. Rem. 1: The report states the bracketed heights above the floor, the non-bracketed values are adapted in order to fit within the measurement grid. Rem. 2: The equivalent number of microphone positions is the length of path/0.5λ, i.e. about $5 \cdot 1/1.7 \approx 3$ at 100 Hz. Rem. 3: A survey through the room is prescribed using L_{pASmax}. The range of pos's included simulates the survey uncertainty, assumed to be 3 dB. Rem. 4: The method does not specify figures, but "prefered distances are 1 m from surfaces however not less than 0.5 m, not to close...". Rem. 5: Quarter/Half the wavelength of the lowest frequency of concern, stated as the 100 Hz values (bracketed 50 Hz) in the table. Rem. 6: The guidelines to low-frequency measurements of ISO 140-3 states the bracketed values, but it was not possible to locate 10 positions in the room using the stated minimum distances. The same distances to walls and floor were used as in the "normal" method (intended for measurement 100–3150 Hz), the separating distance increased to 1.0 m. Rem. 7: Chosen location is at corner with the highest C-weighted level at 0.5 m from the walls, measured 0.5/1.0/1.5 m above the floor.

		Legend in Figures	Type of method
1.	(DK) Delta Akustik J. Jacobssen Report AV 67/96	DK_Delta96	CORN /LF
2.	CEN/TC 126/WG1 N184 AHG2 N23 18 June 1996	CEN_ENG3	DISTR
3.	CEN/TC 126/WG1 N184 AHG2 N23 18 June 1996	CEN_ENG6	CORN /LF
4.	CEN/TC 126/WG1 N175 April 1995 8th Draft	CEN_SUR_Rw	ROOMC
5.	CEN/TC 126/WG1 N175 April 1995 8th Draft	CEN_SUR_Aw	CORN /LF
6.	(USA) ASTM E1574 -95	ASTM_ E1574	DISTR
7.	(DK) Miljöstyrelsens ref. lab. Orientering nr. 3 J. Jacobssen, Nov 1985	DK_MSL85-3	DISTR
8.	(DK) SBI Anvisning 172 1992	DK_SBI92	ROOMC
9.	(DK) Bygningsreglement Bil. 4 1995	DK_BYR4-95	ROOMC
10.	(DK) Miljöstyrelsen Vejledning 6 1984	DK_MSV6-84	DISTR
11.	(SE) SABO Mätblad 22 Förenklad *(Survey method)*	SE_Blad22s	DISTR
12.	(SE) VVS-AMA Normal mätning *(Survey method)*	SE_AMAs	DISTR
13.	(SE) VVS-AMA Noggrann mätning *(Eng. method)*	SE_AMAe	DISTR
14.	(D) VDI 2058 Blatt 1 1985	D_VDI	DISTR
15.	(DK) Denmark TU, JH Rindel "Spatial averaging at LF in a rectangular room" ISO/TC 43/SC 2/WG18 N149 Feb-96	DTU_JHR	CORN
16.	(AUS) ÖNORM S5102 1987 (with extra positions)	ÖNORM_N5	DISTR
17.	(AUS) ÖNORM S5102 1987 4.2.6 LF Noise	ÖNORM_LF	CORN /LF
18.	ISO 140-3 100-3150 Hz. REF. METHOD	ISO140_N	DISTR
19.	ISO 140-3 50-5000 Hz[7]	ISO140_LF	CORN /LF
20.	(SE) SS 025263 1986 A-w fixed pos.	SS-63_Afix	DISTR
21.	(SE) SS 025263 1986 A-w rotating microphone	SS-63_Arot	DISTR
22.	(SE) SS 025263 1996 C-w fixed pos.	SS-63_Cfix	CORN /LF
23.	(SE) SS 025263 1996 C-w fixed corner pos., avoid symm. lines	SS-63_Csym	CORN /LF
24.	(SE) SS 025263 1996 C-w without pos., avoid symm. lines, include pos's 0.2 from the walls	SS-63_Csym-ext	CORN /LF

three corners (see Table II). The results are presented and discussed in detail below.

For some of the methods, the measurement uncertainty does not increase below 125 Hz. It appears that the critical frequency region is at the 63 Hz and 125 octave bands where few first order room modes are excited. The sound field becomes smoother at even lower frequencies and the uncertainty reduced accordingly.

Another interesting observation is that most methods appear to underestimate the sound pressure level (SPL) at LF (except the special corner methods discussed below) although the A-weighted value is not biased. This bias error at LF of the measurement methods is in the order of one standard deviation which adds a new aspect to the old discussion on the shape of the A-weighting network at LF, where a common opinion is that A- weighting suppresses LF too much in relation to the perceived annoyance of the actual sound (noise). Figure 3 suggests that one reason (among several possible) is that as much as 70% of the measurements performed in situ underestimate the actual exposure of sound

Table II. B. Characteristic Requirements of the Methods used. Remarks see caption of Part A.

No.	Min. distance to source (m)	Min/Max distance to room surfaces (m)	Min. distance between positions (m)	Height above floor (m)	Number of positions	Special req. on positions	Averaging
1.	x	0.5/1.0	x	-1 -1.5	2	Aver. of 2 sep. corners	Energetic
2.	1	0.5	1.5	1.0–2.0[1] (1.2–1.8)	3	Distributed. Not on symm. lines	Energetic
3.	1	0.5	1.5	1.0–2.0[2]	6	Distributed. Not on symm. lines	Energetic
4.	1	0.5	x	0.5–1.5 (approx.)	1 swing à 30 sec.[2]	Room Center. Rot. 180°	Energetic
5.	1	0.5 & 1.2 corner	2 (C pos.)	0.5–1.5 (approx.)	3 swing à 30 sec.	2 pos. at room center	Energetic
6.	1	1	1	1.5[2] (1.1–1.3)	1	Position at max. L_{pASmax}	Include all pos's $L_{pA} \leq L_{pA} - 3$[3]
7.	x	1 (0.5)[3]	x	0.5–1.5[4]	3	Distributed. Unequal dist. to surf.	Arithmetic (x)
8.	Close by	x	x	1–1.5[2] (1–1.2)[2]	1	Room Center	Arithmetic (x)
9.	1	1	1.5	1.5[2] (1.2–1.5)	2	Close to Room Center	Energetic
10.	x	0.85 (1.7)[4]	1.7 (3.4)[5]	x	3	Distributed	Arithmetic
11.	1.5	0.5	x	x	3	Distributed	Arithmetic(x)
12.	1.5	1	x	x	1	x	x
13.	1.5	1	x	x	3	Distributed	Energetic
14.	x	1.0/1.5 (1.2)[2]	x	1.5 (1.2)[2]	1	Repr. pos. (NB modes)	x
15.	x	0.01 and LWH/3	x	0.01 and LWH/3	2	Close-to-corner and at LWH/3	Arithmetic
16.	x	1	x	x	5	x	Energetic
17.	x	<0.10	x	<0.10	3	Corners only	Energetic
18.	1.5	0.5 (0.7)[2]	0.7	0.5 (0.7)[2]	5	Distributed	Energetic
19.	spec	0.5 (1.2)[6]	1.0 (1.4)[7]	0.5 (> 1.2)[7]	10	Distributed	Energetic
20.	spec	0.5	0.7	>0.5	3	Distributed	Energetic
21.	spec	0.5	0.7	>0.5	1	x	Energetic
22.	spec	0.5	0.7	>0.5	3	1 pos. = corner at LpCmax[7]	Energetic
23.	spec	0.5	0.7	>0.5	3	1 pos. = corner at LpCmax[5]. Not on symm. lines	Energetic
24.	spec	0.2	0.7	>0.5	3	Not on symm. lines	Energetic

to the inhabitants as compared to the true room average. This conclusion is emphasized if the measurement results are compared to the maximum level in the room.

The measurement uncertainty expressed as the reproducibility R is defined in ISO 140-2 as 2.83 * standard deviation, i.e. R is approximately 3 times the values shown in Figure 3b. The general purpose methods intended mainly for the measurement of A-weighted sound pressure levels show an unacceptable scatter. Standard deviations up to about 5 dB have been found, the uncertainty may therefore be up to

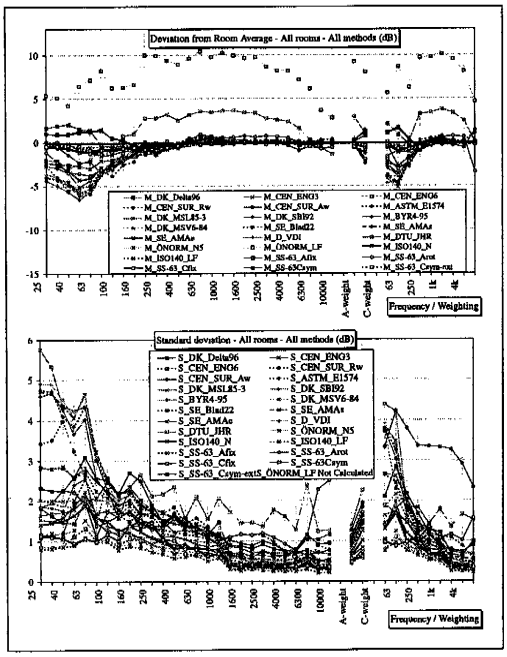


Figure 3. Overviews. The embedded legend refers to Table II. Frequency axis show third octave bands 25 Hz–10 kHz, A- och C-weighted, octave bands 31 Hz-8 kHz. (a) Upper: Ensemble mean deviation from room averages (dB) calculated by simulating the measurement methods. (b) Lower: The mean standard deviation. The measurements were made in the 10 rooms according to Table I. The result graphs are also presented in smaller groups below and in the Appendix C of the project report [3].

15 dB, and a systematic under-estimation of the C-weighted and LF third octave bands. At frequencies higher than the 250 Hz octave band, most of the methods work satisfactory except for some special corner methods. Arithmetic averaging increases the uncertainty at low frequencies. Results from each room is presented in Appendices C and D of the project report [3].

2.3.2. Results - dedicated low frequency methods

Some of the methods indicated by "CORN/LF" in Table II are special corner methods, i.e. they utilize the increase of SPL in the corners and thereby avoid the regions in the room with extremely low SPL (with the nodal lines of the modes). This approach seems at the first glance to be a perfect way to avoid the regions in the room with low SPL. An example of such an idealized sound field (one resonant mode 1-1 at 67 Hz) of a small reverberation chamber and the actual sound field (two resonant modes excited simultaneously) are shown in Figure 4 and 2 respectively.

The examples indicate that any method that leaves the choice of corner to be used for the measurement open will show a larger scatter than methods that choose a corner in a deterministic manner, e.g. the corner with the highest SPL.

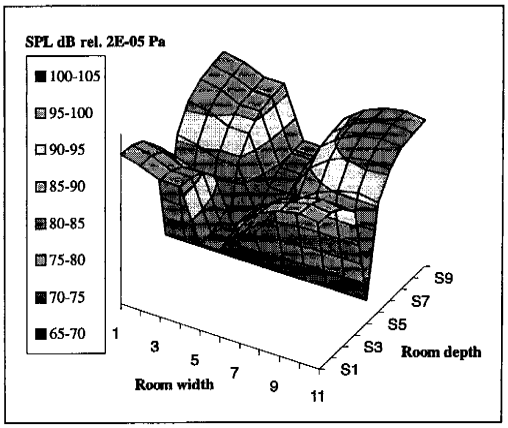


Figure 4. Idealized sound field at 67 Hz (mode 1-1). Compare with the Figure 2 that shows the measured sound field in the 63 Hz third octave band (were both modes 1-0 and 1-1 are excited).

The Figure 5 (below) demonstrates that this difference in performance of the corner methods did affect both the scatter and the deviation from the room average. This conclusion is in agreement with the findings by Chu and Warnock [4].

2.3.3. Results - methods with distributed positions

This group of methods specify a random choice of microphone locations within limits with respect to the distances to the walls and floor as well as the minimum distance between the microphones (see Table II). On the average, the A-weighted SPL is not biased but shows an uncertainty in the order of ±2 dB (Reproducibility R with 95% confidence). At LF, the bias is negative which means that the methods tend to underestimate the SPL as compared to the true room average (of all measurement locations).

2.3.4. Results - methods with positions in the room center

This group of methods specify a random choice of a single microphone location close to the centre of the room (see Table II). On the average, the A-weighted SPL is not biased but shows an uncertainty in the order of ±2 dB (Reproducibility R with 95% confidence). At LF, the bias is negative which means that the methods tend to underestimate the SPL as compared to the true room average (of all measurement locations). Consequently, the C-weighted SPL is biased in the order of 1–2 dB.

3. Inter-Nordic Round Robin comparison

3.1. Design of a modified corner method to be tested

A few proposals for modifications of the draft CEN methods [5, 6] were discussed by the project group to design a new test method:

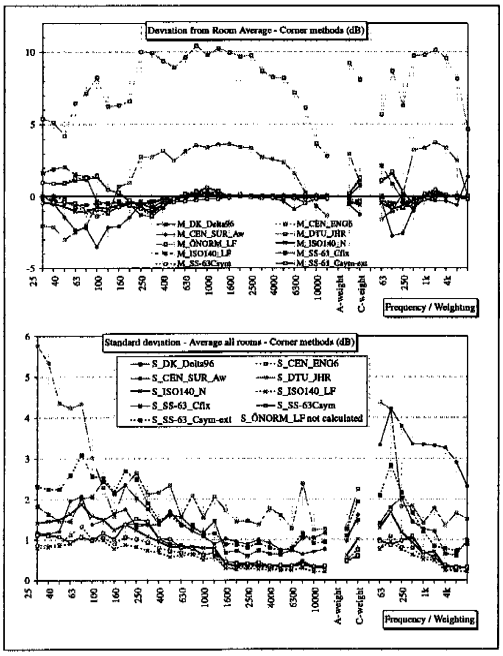


Figure 5. Legend see Figure 3. (a). Ensemble mean deviations from the room average using 8 special methods for low frequencies and 2 "normal methods". The 2 upper curves (M_ÖNORM_LF and M_DTU_JHR) overestimate the room average (they are explicitly intended for noise at very low frequencies only). The new Swedish standard with a special LF method (SS63_Cfix) appears to overestimate slightly as compared to the room average. The ISO 140_LF did not overestimate at LF in spite of the obstructed requirement on distances to the walls and floor (chosen smaller than the stated minimum values). (b). Ensemble standard deviations calculated by simulating 8 special methods for low frequencies. The new Swedish standard with a special LF method (SS63_Cfix), the ISO_140_LF and the CEN_SUR_A-w methods have very good reproducibility (low standard deviation) compared to other methods.

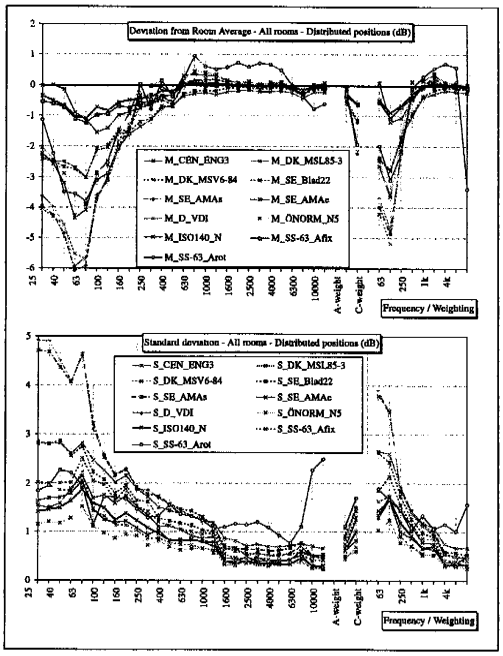


Figure 6. Legend see Figure 3 and Table II. (a) Top: Ensemble mean deviation from room averages calculated by simulating the distributed measurement methods. (b) Bottom: The mean standard deviation. The measurements were made in the 10 rooms according to Table I. Methods using single positions shows large uncertainty at LF but appear to work reasonable well above the 125 Hz octave band.

- moving microphones/swinging were included for "room position" measurements only when the sound is continuous or repetitive (steady)
- background noise from cloths, mechanical sounds etc. when the microphone is moved must always be controlled by the operator at the measurement site. The microphone can be paused at various stops along a scanning path during measurements. All handling of the instrument must be proved to cause background noise well below the noise of interest
- the concept of choosing " microphone positions located where habitants actually occupy the room" as stated in the Swedish standard SS 02 52 63 was rejected. The room positions should preferably be chosen randomly in the reverberant field away from the boundaries of the room. The recommendation to avoid the symmetry lines in the draft standard [6] does not seem to work well and was abandoned
- the concept of including a special corner position selected by means of a quick survey was decided on. It was also decided to try out the concept of assessing the boundary conditions in the room and selecting the "best" corner in case the sound is irregular and there is no possibility to survey the corners by measurements. This was thought to be an improvement rather than to leave the choice open.

The findings were applied to design a new method, which was tested by the members (as described below):

Guidelines given to the participants of the comparison measurements

1. Look for the corner which can be assumed to have the highest sound pressure levels (SPL) at low frequencies (LF).
   "Choose the most apparent corner with the acoustically hardest surfaces and which may be assessed to have the highest low frequency sound pressure level" Note: acoustically hard surfaces are built by heavy building construction material and have the least amount of openings, doors, lockers, windows, sound absorbing or diffusing items (furniture, textiles etc.).
2. Calibrate the analyzer

Table III. Room cases used for inter-laboratory tests.

Room/Case "Case ID"	Dim (m)	Furniture etc.	Excitation
Reverb.room: "Impact-lab NAD"	6.2 x 5.2 x 3.6	Without diffusers, hard surfaces.	Impact machine on concrete roof (high frequency noise)
Reverb.room: "Impact-lab WAD"	- " -	With additional gypsum boards and thick piles of mineral wool with plastic cover	As above
Office (large): "Office WAD"	4 x 3 x 2.4	Tables and chairs. Concrete slabs, sound absorbers class A in ceiling. Plastic carpet. Gypsum board walls, windows	Loudspeaker enclosed inside locker, close to wall, pink noise.
Office (small): "Office NA"	2.5 x 3 x 2.4	As above, without absorbers in ceiling.	As above
Living room: "GV-LivRoom"	5 x 4 x 2.5	Lightweight timber house construction, furnished	Loudspeaker enclosed in small room below (MLS noise)
Bed room: "GV-BedRoom"	3.5 x 2.4 x 2.5	Lightweight timber house construction, furnished	As above

Table IV. Results of assessment of corner with highest L_{pC}.

Participant:	VTT	NBI	SP-1	SP-2	Delta	IBRI	$L_{pC\,m}$
	Impact-lab WAD (high freq. spectrum, absorbers)						50 %
Co1				x	x	x	85.8
Co2	x	x	x				86.4
Co3							85.8
Co4							85.0
	Impact-lab NAD (high freq. spectrum, no absorbers)						50 %
Co1				x	x	x	90.3
Co2	x	x	x				89.9
Co3							90.1
Co4							89.9
	Office-WAD						17 %
Co1			x	x		x	93.3
Co2					x		94.8
Co3	x	x					90.8
Co4							94.7
	Office-NAD						0 %
Co1			x	x		x	78.3
Co2		x					81.1
Co3							82.2
Co4	x				x		75.8
	GV-LivRoom						50 %
Co1		x					78.3
Co2							81.1
Co3			x	x		x	82.2
Co4	x				x		75.8
	GV-BedRoom						17 %
Co1			x				77.1
Co2		x					78.5
Co3							77.7
Co4	x			x	x	x	78.0

3. Select the appropriate directory (for the room case) and start the acquisition software. Select your sheet (labeled with the acronym of your lab). Position the cursor at 25 Hz, corner no 1. Data will be transferred from the analyzer to the Excel-sheet, follow the instructions on the screen.
4. Position the microphone in the first corner 1. Close the door. Turn on/off the noise, check that the signal to noise ratio (S/N) $\geq$ 6 dB in each frequency band. Measure with and without the noise, read S/N column. Increase SPL if necessary or adjust the equalizer (if there is anyone in the sound system). Make sure that the sound is continuous, e.g. that there is no voltage drop of the amplifiers.
5. Measure all corners (See the Table V and the footnotes of this table): Scan 0.5/1.0/1.5 m, choose the position with

Table V. Principles for the measurement of room average sound pressure levels.
Remarks: Rem. 1: Measure the sound pressure level at corners 0.5 m from the walls and 0.5 m from the floor if feasible. If this location is not feasible due to protruding furniture, obstacles etc., increase the height to 1.0 m (if necessary to 1.5 m) above the floor. Move away small protruding items that do not affect the sound field if necessary. Keep microphone at least 0.2 m away from any obstacle. Measure L_{pCeq} as stated. Measure optionally in frequency bands (in parallel or separately) or with other frequency weightings. Rem. 2. Choose room positions 2 and 3 (2-6 in the precision grade) in the reverberant field of the room, at least 1.5 m from each other, 1.5 m from the pos. 1 and any direct sound source, 0.5 m from any room surface, 0.5-1.5 m above floor level. It is allowed to use a rotating or swinging microphone with radius $\geq$0.8 m in place of two fixed room positions, provided that the same conditions on distances are applied (see Rem. 1).Determine sound emission from a direct sound source inside the room separately (do not include in room average): measure 1 m in front of the source 1.5 m above floor level, or in case the source is placed in the ceiling, measure 1.5 m above the floor directly below the source. Rem. 3. Calculate the energetic room average of the sound pressure levels obtained from individual positions and sound events. The single room position and twice the average of 2 room positions (six for the precision grade) give the room average sound pressure level: $L_p = 10\log_{10}[(p^2_{\text{corner}} + 2\langle p^2_{\text{room}}\rangle)/(3p^2_{\text{ref}})]$, *) where p_{ref} is $2\cdot 10^{-5}$ Pa and $\langle p^2_{\text{room}}\rangle$ is $[p^2_{\text{pos2}}]$ for a single room position, $[(p^2_{\text{pos2}} + p^2_{\text{pos3}})/2]$ for two room positions, $[(p^2_{\text{pos2}} + \cdots + p^2_{\text{pos6}})/6]$ for six room positions. *): This weighting of positions can easily be accomplished by adding -1.76 dB to the $L_{p,\text{corner}}$ and $+1.25$ dB to $L_{p,<\text{room}>}$. Rem. 4. where $(s^2_{\text{source}} + s^2_{\text{lab.}})$ of continuos steady noise was estimated within the pre-study and the inter-laboratory test, given within brackets. $s^2_{\text{equipment}}$ is estimated to $\leq$0.5 dB. Rem. 5. Fluctuations of the source will increase the measurement uncertainty, particularly of L_{pXFmax} · estimates.

No.	Type of Sound:	Method/Grade: Survey (S)
1.	Steady, constant sound Steady, intermittent sound Source(s): Several stable sources running simultaneously, or single sources, e.g. technical installations such as fans, pumps, transformers, engines etc. Measured: L_{pXeq}. T_m L_{pXFmax} (where X is the frequency weighting and T_m the measurement time).	S1. Measure L_{pCeq} according to Rem. 1 at all corners during a full operating cycle, at least 30 seconds. Select the measurement with the highest L_{pCeq} as position 1. Measure at room positions 2 and 3 chosen according to Rem. 2. Calculate the room average of the positions according to Rem. 3
2.	Repeatable sound events from a single technical installation. Source: e.g. WC, Lift etc. Measured: L_{pXFmax}, optionally also L_{pXeq}, T_m (No. of events) or $L_{pXeq,1s}$ (sound exposure level) (where X is the frequency weighting).	S2. Whenever feasible, measure according to S1 using 1 sound event in each position. If not (e.g. if the sound event is difficult to repeat), a simplified procedure may be applied: Measure $L_{pCeq,1s}$ as described in Rem. 1 during one event at the corner with the apparently most reflecting surfaces of the room. If $L_{pC} - L_{pA} \leq 5$ dB (If not, the procedure S1 must be followed), it is allowed to include this measurement as position 1 without checking the other corners. Add a single room position 2 according to Rem. 2. Measure L_{pCeq}, 1s of two sound events in position 2. Calculate the room average of the positions according to Rem. 3.
3.	Irregular, not reproducible sound events. Source(s): Not identified. Measured: L_{pXeq}, T_m, L_{pXFmax}, optionally $L_{pXeq,1s}$ (sound exposure level), (where X is the frequency weighting and T_m the measurement time).	S3. Follow the simplified procedure S2. Measure at least during three sound events.
4.	R. Reproducibility (from ISO 140-2, 5725) (Rem 4, 5): $R_{95\%} = 2.83\sqrt{s^2_{\text{source}} + s^2_{\text{lab.}} + s^2_{\text{equipm.}}}$	SR. L_{pAeq}: $R_{95\%} = 4$ dB (1,0) *) L_{pCeq}: $R_{95\%} = 5$ dB (1,5) *) $L_{p\Delta eq}$: $R_{95\%} = 6$ dB (2,0) *) **) **) Only if position 1 is chosen according to S1 **) Δ denotes frequency bands (octave or third octaves) below 200 Hz.

the highest L_{pCeq8s}. Measure 30 seconds, again look carefully for disturbing background noise events.

6. Measure 2 room positions randomly with the following restrictions: Keep the microphone
   - at least 1.5 m away from each other
   - at least 1.5 m away from the selected corner position
   - at least 1.5 m away from any direct sound source
   - not closer to the walls than 0.5 m
   - between 0.5 and 1.5 m above the floor.
7. Repeat step 6, try to achieve the lowest SPL possible within the restrictions in remark 2 of Table V.
8. Repeat step 6, try to achieve the highest SPL possible within the restrictions in remark 2 of Table V.
9. Make sure that the data is stored in the right positions and that the A- and C-weighted values and the $[x, y, z]$ position data are appropriately filled in. Always note the filename and the A- and C-weighted levels in the column of the Excel-sheet, this is extremely important in case the transfer of files takes place later.

3.2. Experimental tests in 6 rooms

6 different room cases with various types of excitations were chosen for the test. Each room case was measured independently by three members using the method described in 3.1.

Table V. Continuation.

No.	Method/Grade: Engineering (E)	Method/Grade: Precision (P)
1.	E1. Measure and calculate according to S1. with the following additional requirements: Measure at position 1 parallel to or inbetween each measurement in the reverberant field (positions 2 and 3). The sound pressure level can not be determined with E-accuracy if the variation of the source strength at position 1 between two consecutive measurements ($\geq$30 sec.) exceeds L_{pAeq} 1.0 dB or $L_{p\Delta eq}$ 1.5 dB. Δ denotes frequency bands (octave or third octaves). The stated limits do not include uncertainty caused by time variations of the sound.	P1. Measure and calculate according to S1. with the following additional requirements: Use a real time parallel third-octave band analyzer with $\geq$2 channels. Use one channel for the corner position 1. Use the other channels for 6 room positions. Measure at positions 2–6 distributed in the room according to Rem. 2. Measure the energetic average of two or more operating cycles in each microphone position (each $\geq$30 sec.). The sound pressure level can not be determined with P-accuracy if the variation of the source strength at position 1 between two consecutive measurements ($\geq$30 sec.) exceeds L_{pAeq} 0.5 dB or L_{pDeq} 1.0 dB (See remark E1).
2.	E2. Measure according to E1. At least one representative sound event must be used for each corner measurement. Select the measurement with the highest L_{pCeq} as position 1. Measure again at position 1. check the repeatability criteria of E1. If fulfilled, average the two results at position 1. Measure at positions 2 and 3 according to E1. Calculate room average according to Rem. 3.	Not applicable.
3.	Not applicable.	Not applicable.
4.	ER. L_{pAeq}: $R_{95\%}$ = 3 dB (0.75) L_{pCeq}: $R_{95\%}$ = 4 dB (1.0) $L_{p\Delta eq}$: $R_{95\%}$ = 5 dB (1.5) *) *) Δ denotes frequency bands (octave or third octaves) below 200 Hz.	EP. L_{pAeq}: $R_{95\%}$ = 3 dB (0.5) L_{pCeq}: $R_{95\%}$ = 4 dB (0.75) $L_{p\Delta eq}$: $R_{95\%}$ = 5 dB (1.0) *) *) Δ denotes frequency bands (octave or third octaves) below 200 Hz.

3.3. Results - overview

The proposed procedure with a visual inspection and assessment of the corner with the highest low frequency sound pressure level in each room did unfortunately not give unambiguous results. The table 4 shows the detailed results. The bold $L_{pC'}$ result corresponds to the correct choice. The percentage to the upper right shows the percentage of members who found the 'correct' corner. It was, however, concluded that the procedure could be included in case low frequency sound does not dominate the spectrum of the noise to be measured, since it may improve reproducibility slightly compared to allowing the choice of corner free (which gives an arbitrary choice).

The measurement results from one selected corner position and 6 room positions chosen according to 3.1 were used to form three types of averages. For the survey grade measurement, only one room position was used in each average, resulting in 108 averages (6 rooms, 6 positions, 3 operators). For the engineering grade, two room positions were used in each average, 54 averages in all. For a precision grade, all 6 room positions were used in each average, 18 averages in all. The weighting factor of the room positions were the same in order to maintain the proper balance between the corner and the room positions. A weighting factor of 2 was found in the simulation study to yield a low bias error (compared to the room average) and to prevent a too large influence of the corner position. Thus the single room position and twice the average of 6 room positions were used in the final average:

$$L_p = 10\log_{10}\frac{p^2_{\text{corner}} + 2\langle p^2_{\text{room}}\rangle)}{3p^2_{\text{ref}}}, \tag{4}$$

where

$$p_{\text{ref}} = 2\cdot 10^{-5}\ \text{Pa}, \tag{5}$$

$\langle p^2_{room}\rangle$is

p^2_{pos2} for a single room position, (6)

$(p^2_{\text{pos2}} + p^2_{\text{pos3}})/2$ for two room positions, (7)

$(p^2_{\text{pos2}} + p^2_{\text{pos3}} + \ldots + p^2_{\text{pos6}})/6]$ for six room pos. (8)

The bias 'error' was calculated by a comparison between the measured average and the spatial average of all six room positions (not including the corner positions). The result is presented in Figure 8. The results from each room are given in [3].

3.4. Conclusions - outline of new methods with three grades of accuracy

From the results of the inter-laboratory tests, it was decided within the project group to propose guidelines for the choice of measurement positions in a room with three grades of accuracy – survey, engineering and precision grades. To allow

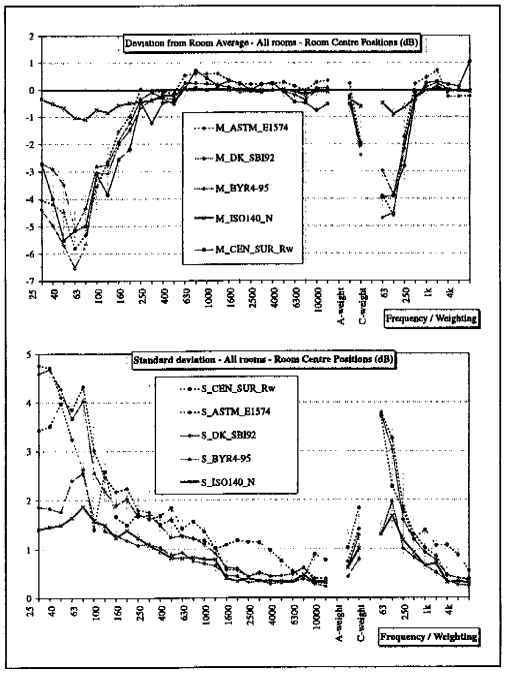


Figure 7. Legend see Figure 3 and Table II. (a) Top: Ensemble mean deviation from room averages calculated by simulating the room center measurement methods. (b) Bottom: The mean standard deviation. The measurements were made in the 10 rooms according to Table I. Methods using single positions shows large uncertainty at LF but appear to work reasonable well above the 250 Hz octave band.

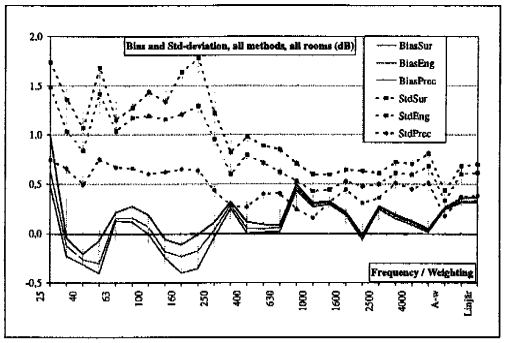


Figure 8. The average deviations of the survey, engineering and precision methods. The bias denotes deviation from the average of the six room positions, calculated from all measurements (excluding the corner measurements). The signal to noise ratio at 25 Hz was $\leq$6 dB in several room cases. The results show that very accurate determinations can be made using the proposed concept of including a measurement point in a corner, selected from the highest L_{pC} value.

for a precise determination of a specific sound source (e.g. a service equipment, ventilation system etc.), also the operating conditions must be strictly verified in the more precise methods to obtain the desired accuracy. The below Table V concludes the findings at the project meeting, as documented at the meeting with the project group.

Note: The Table V is very concentrated and is obviously too complex to be used as a stand-alone method description. It is merely intended as an overview of the principles for the design of new methods.

An estimate of the measurement accuracy is included for each method. It has been calculated according to ISO 140-2, based on a conservative estimate of the expected standard deviation found during the inter-laboratory tests and the simulation study. It also includes an estimated standard deviation of 0.5 dB to account for uncertainties of a measurement equipment. It does not include uncertainty caused by time variations of the sound.

4. Conclusions

The main conclusions from the simulations are that most of the existing methods

- give large measurement uncertainties at low frequencies (poor reproducibility)
- underestimate the room average level in the order of one standard deviation or more whereas it is preferred to have the opposite tendency to correlate measurement results with subjective annoyance
- appear to be cumbersome to apply, have ambiguous or complicated instructions, some are even impractical
- special corner methods do not perform well unless they specify which corner to use for measurements because the sound fields in the rooms are not symmetrical
- rotating microphones do not improve the reproducibility significantly compared to several fixed positions distributed in the room
- 5 or more fixed positions distributed in the room perform well but are impractical to apply, especially for the measurement of single noise events that are difficult to repeat.

The general purpose methods intended mainly for the measurement of A-weighted sound pressure levels show an unacceptable scatter (reproducibility $R > 20$ dB at low frequencies) and a systematic underestimation of the C-weighted, octave and third octave band values below 200 Hz. At frequencies higher than the 250 Hz octave band, most of the methods work satisfactorily except for some specialized corner methods. Arithmetic averaging increases the uncertainty at low frequencies. Results from each room are presented in Appendices A-C. The sound pressure levels measured in each room are available for download from http://www.sp.se/pne/acoustics.

Thus the existing methods are not appropriate for the determination of the sound pressure levels in rooms at low frequencies. Some new methods based on moving microphones with large radii, or many fixed distributed positions or the use of a specified corner location all perform satisfactorily,

both with respect to deviation from the true room average (bias error) and to scatter (reproducibility).

In the second phase of the project, the project group outlined a new method, based on the concept of scanning the corners of the room for the highest C-weighted level (as in the present Swedish standard SS 02 52 63), and including this measurement in the spatial average. It seems that the concept of including the "strongest" corner reduces the measurement effort, reduces the scatter and improves the correlation to the room average. This method was tested in an Inter-Nordic Round Robin comparison with 5 laboratories, where very good reproducibility was achieved. The bias error (defined as the deviation from the average of 6 room positions measured in the central part of the room) was very low. These findings seem to agree with results obtained by other researchers [1] and consultants [2] who have made their own reproducibility tests in rooms with SS 02 52 63 as well as with other methods.

Within lectures given at SP about practical measurement techniques on indoor clima, staff from various Swedish environmental protection agencies have learned the method with a reasonable amount of preparation work. The measurement reproducibility obtained in the same room with the same sound source was well within the limits stated in Table V. The staff commented, that they accept a more complex measurement method (i.e. with the scanning-of-the-corners-technique) in order to improve the reproducibility of the measurement results.

References

[1] J. Jacobssen: Lavfrekvent støj, infralyd og vibrationer i eksternt miljø. notat 2. rumsakustiske forhold ved lave frekvenser. Report AV 67/96. Delta Akustik & Vibration Lyngby, 1996. (In Danish).

[2] B. Ottosson: Utvärdering av mätmetod för låga frekvenser. konsekvenser. Report TR 95234-R03. KM Akustikbyrån, Solna, 1996. (In Swedish).

[3] C. Simmons: Measurement of sound pressure levels at low frequencies in rooms. Comparison of available methods and standards with respect to microphone positions. SP REPORT 1997:27. SP, Borås, 1997. ISBN 91-7848-685-8. ISSN 0284-5172.

[4] W. T. Chu, A. C. C. Warnock, J. D. Quirt: Laboratory methods of testing for rating low frequency sound emission of air conditioning equipment. National Research Council Canada. Client Report CR-5963 Final for the ASHRAE (American Soc. of Heating, Refrigeration and Air Conditioning), December 1993.

[5] ISO/TC 43/SC 2 N 592: Building acoustics: Field measurements of airborne and impact sound insulation and of equipment noise - Survey method. Received at Byggstandardiseringen (the Swedish Standardization Body). 11th Draft standard July 1997., 8th September 1997.

[6] ISO/TC 43/SC 2 N 593: Acoustics - Measurement of noise from service equipment in buildings - Engineering method. Received at SP (the Swedish National Research and Testing Institute). Draft standard August 1997, 17th September 1997.

Paper V

A handbook on the management of acoustic issues during the building process

Klas G. Hagberg,
ÅF Sound & Vibration
Box 1551, SE-401 51 Göteborg, Sweden
klas.hagberg@afconsult.com

Christian Simmons
Simmons akustik & utveckling AB/Luleå Univ. of Technology
Krokslätts Fabriker 1, SE – 431 37 Mölndal, Sweden
christian.simmons@euromail.se

ABSTRACT

A new handbook has been published by the Swedish National Board of Housing, Building and Planning. This handbook describes the building process from an acoustical point of view. It focuses on the conversion of functional requirements on the performance of the building to appropriate designs of a building. This type of requirement allows all kinds of solutions to be applied, but is also requires coordination of acoustic issues between the parties involved during the entire building process. Hence, the handbook addresses detailed information to each party. Functional requirements and acoustic issues are complex by nature, because they affect many building elements, they are handled by several parties and they must be considered during several phases of the building process. Typical errors come from building designs (floor plans), product designs (input data of elements), calculation models, quality of workmanship (during the construction phase) and uncertainties in field measurements. The aim is to help the commissioner manage the responsibility for these issues. The handbook also covers a large field of practical applications to support the acoustic expertise. It is expected that this handbook will encourage developers and contractors to deal with acoustic issues more efficiently. If the noise environment is not considered in the design process for new residential areas and other building facilities, the satisfaction of tenants, the health costs for the society and the building values will be affected. If verifications are made only at a late stage of the building process, errors are normally discovered too late. They are then expensive to correct for and it is difficult to find out who is responsible. When the verifications are made effectively during the process, costs are minimized.

1 INTRODUCTION

This paper summarizes the content of a new handbook, which includes; a description of the process to handle acoustical issues during the building process; practical advices to all parties involved in the process and interpretations of functional requirements in sound classifications standards that are referred to by the Swedish building regulations. However, this paper does not discuss scientific theory. The aim is rather to describe a practical way to deal with acoustics throughout the building process, from the interpretation of the functional requirements, the early stage design, the purchases of building elements to the finalized building.

The modern building process is complicated. For those who deal with acoustic issues in the design phase or the construction phase, this is obvious for several reasons. New buildings are often erected at complicated sites in the city centres. Hence, they are often exposed to high sound levels and ground vibrations from various types of traffic. High requirements on sound insulation between the interior spaces are frequent, e.g. between residential apartments and premises for public activities (shops, restaurants, theatres, cinemas etc) and these requirements tend to be raised further in future. Furthermore, new architecture and new building products are often suggested, which claim a lot of knowledge to handle since empirical experience is not always at hand for these specific solutions.

Since a few years, there is a need to transfer acoustic knowledge directly to our building industry, since the teaching of building acoustics at our universities has been significantly reduced. It is too expensive to retain acoustic laboratories at the universities, since they are not efficiently used, hence converted and used for other purposes. Furthermore, the governmental grants to research and teaching have been reduced which has resulted in fewer civil engineers graduated with even basic knowledge in acoustics.

At the same time, modern buildings become more and more complicated, and the building acoustic demands from inhabitants and commercial developers are increasing. Lightweight structures (e.g. by wood or steel) are being used more frequently in multi storey residential buildings, which present large challenges to the acousticians.

The possibility to use various building products is now easier than some decades ago, partly because the requirements are based on performance of the building (or spaces therein) instead of the properties of individual products. Performance based building codes may be regarded as an "open system" compared to codes based on specific dimensions and constructions.

However, an important disadvantage of a performance based building code is the need for conversion from the performance of products to the expected performance of buildings. Requirements on dimensions and constructions are more "straight forward" to apply and to verify by inspection *in situ*. However, the advent of EN 12354 [1] and extensive laboratory tests have helped the acousticians making rational choices and decisions with respect to combination of products, at least in those cases where the standardized calculation models are applicable. There are now an increasing number of innovative products and structural elements that might be combined in order to meet the requirements stated by the client or the national building codes.

Furthermore, the requirements are often changed. In Sweden (as well is in some other countries), the requirements by authorities or clients normally refer to the sound classification standards or similar publications. The Swedish standard SS 25267 [2] addresses requirements for dwellings and the SS 25268 [3] addresses spaces in hospitals, schools, offices, hotels and institutional premises. The idea behind a classification system is to offer the developer too choose a level of acoustic quality (sound class) that is appropriate for the actual performance level considering the acceptable cost level. The sound class may vary in different projects, from renovation of old buildings (low sound class) to very high ambitions (luxury apartments).

Acoustic issues affect many building constructions, several parties must handle them and they influence several phases during the building process. Typical errors come from building design (floor plan), product design (data), calculation models, assemblies in the building (construction phase) and uncertainties in field measurements.

1.1 A new handbook

On the initiative of the National Board of Housing Building and Planning (Boverket), a new handbook has been issued, in an attempt to facilitate the management of building projects with respect to the acoustic issues. The handbook is written to coop with the following needs:

- to describe how the commissioner (e.g. a developer or a proprietor) can specify the responsibility for different parties involved during the building process. Each party then gets specific targets to facilitate his handling of acoustic issues.
- to present interpretations and application examples on the Swedish sound classification standards, based on a large number of real questions and detailed examples from the building industry, universities and consultants.

- to complement other guidelines and advisory notes from the National Board of Housing Building and Planning used by local authorities.

The handbook consists of seven sections:

- Sections 1 and 2 address information to all participants in the building process who may come in contact with acoustic issues, for example proprietors, developers, authorities, designers, manufacturers, building contractors, experts, quality controllers etc. They give general background information and a description of which parties should take responsibility during each phase of the building process.
- Section 3 recommends the commissioner to engage an acoustic expert to monitor all phases of design, drawings, building details at the site, as well as the verification measurements in partly finalized or in the finalized building. As a result, an acoustic documentation is assembled. This documentation is a living document that may support the other parties of the project team during the building process.
- Section 4 is primarily addressed to experts within acoustics, involving detailed advices on risks and interpretation aspects on the sound requirements.
- Section 5 gives information to manufacturers on how they should test and present the acoustical technical properties of their products, as well as supplementary information on how to secure that the product fits to connecting structures, handling issues, mounting advices etc.
- Section 6 gives general advice to building contractors. The advices address several aspects which should be considered to avoid raised costs due to poor workmanship and a lack of precision during the construction phase.
- Section 7 clarifies the most important tasks to verify the acoustic performance of the building. It has become clear that the international standards for sound testing at the sites (ISO 140-series) are not detailed enough. Uncertainty may be reduced with complementary instructions, e.g. to minimize arbitrary choices of measurement locations etc.

However, the handbook does not cover all conceivable acoustic problems, nor does it give a general review of theoretical acoustics. It is intended to facilitate the management and the probability to fulfil the intended sound class, and to clarify responsibilities to all parties involved in each stage. It does give reference to papers and books on theory etc. that may be of interest to some parties, e.g. manufacturers of service equipment or building elements.

It is a well known fact that if technical aspects, i.e. acoustics, are *not* considered at an early stage this might lead to raised costs in the end of the building project, as illustrated by the figure 1.

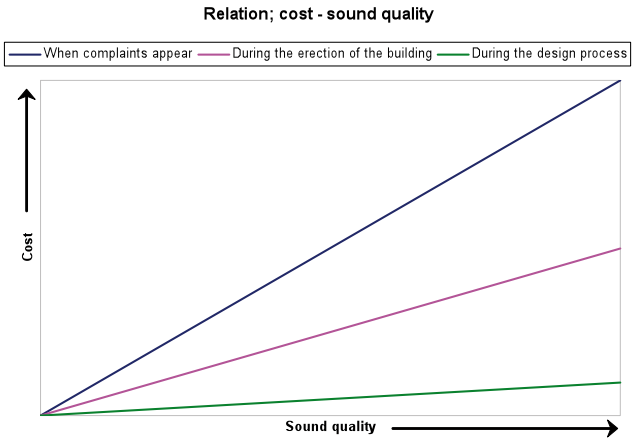


Figure 1: The relation between costs for acoustic (or other) measures and sound quality depending on when the technical issues are considered during the building process.

2 THE COMPLEXITY OF THE BUILDING PROCESS

There are often conceptual confusions within the building industry and between the parties of a project process, with respect to the variety of type of agreements, c.f. figure 2. In an attempt to simplify the process the purposes of different participants in the process are emphasized, no matter whom is responsible for a specific task at a specific time during the progress of a project. The handbook describes which parts should be managed and by whom: the developer, the experts, the designers, the manufacturers, the building contractors or the authorities.

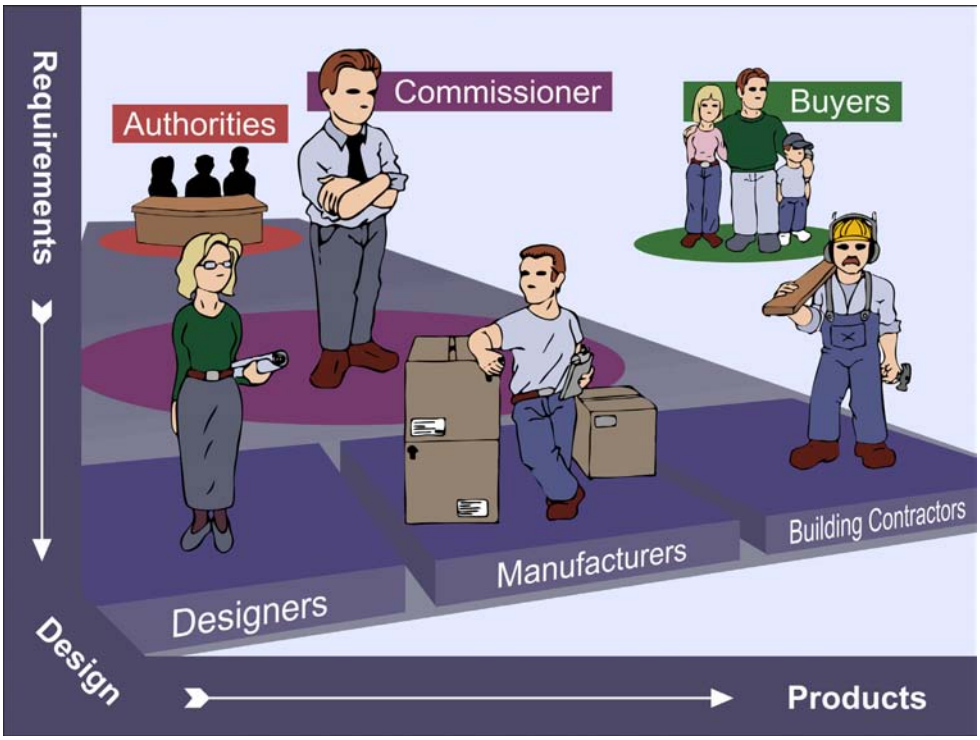


Figure 2: The complex matrix of actors involved in a building project. General performance based requirements (sound class) stated by the Authorities and the Developer must be interpreted by the Designer to constructions and to products. The Manufacturers must present correct input data to the Designer. The Contractor must follow all instructions carefully and handle risk constructions consciously. The final Buyer (or tenant) is often not involved at all during the planning, design and construction phases.

3 THE STRUCTURE OF THE HANDBOOK

3.1 Acoustic documentation – created by the expert

Frequently, there is no acoustician involved during the very early phases of a building process. They may be commissioned during the latest stage of design process or sometimes just to perform measurements in the finalized building or when problem occurred. However, the handbook advises the commissioner to engage an acoustician during all phases of the project. Then, all acoustical risks may be clarified and handled early, and all parties involved may be assisted by the acoustic documentation, updated throughout the process. Furthermore, an acoustic consultant knows where the acoustic efforts are most beneficial and may guide the client through the building process. The communication with the authorities is made easier by the assistance of an experienced acoustician.

The expert should establish an acoustic documentation with a structure described in section 3 of the handbook. In general the documentation may cover the following topics:

- ***Part 1*** specifies the sound requirements established by the developer (particularly if they deviate from the recommendations given by the sound classification standards). In this phase, the input data regarding exterior noise levels should be specified, as well as the façade elements (walls, doors and windows) that must attenuate noise from the exterior. In public premises, the requirements may be adapted to fit the needs of the

current clients/tenants. In multi storey residential buildings, relieves of the requirements may be appropriate, for example on the impact sound insulation of staircases that are only intended for evacuation purposes.

- ***Part 2*** contains recommendations for the design of the building (documented by drawings and product descriptions) such that it fulfils the current sound class (requirement). The risks should be highlighted, considering known issues with the actual structural elements (light weight or heavy structure, prefabricated or in-situ manufactured etc) as well as the contained building products.

- ***Part 3*** describes the procedure for review and verification within different stages of the project.

3.2 other sections

Section 4 is primarily addressed to designers and acousticians and it has the same basic structure as the Swedish sound classification standards. The content of section 4 gives backgrounds, interpretations and examples in order to increase the understanding and to facilitate the application of the standards. Its content is written on the basis of real questions and contain statements that faces frequent attitudes by the building industry, universities, consultants etc. As an example, a developer is certainly free to pick single requirements from various acoustic properties in the different sound classes as long as the minimum national requirements are fulfilled. But the handbook explain why this is not recommended, i.e. it explains that the perceived sound level will be determined by the weakest part of the building. Hence, in some respects the building will be either worse or better than expected which is, of course, not cost efficient.

Section 5 describes current requirements, standards and methods applicable to manufacturers in order to deliver product data usable in the calculation standard series ISO EN 12354 (equal to ISO 15712) [1] which are of particular significance. The section also emphasizes the importance of good workmanship of field adapted assembly instructions, e.g. structures made of lightweight material.

Section 6 addresses building contractors and involves, amongst others, description of risk level, description of sensitive details, typical acoustical problems with regard to service equipments etc. Such descriptions are cumbersome to establish, because the variety of constructions and possible problems in intersections makes it virtually impossible to cover all risks that may occur. Hence, also the contractor must have some basic understanding of acoustics and be able to identify risks that have not yet been described.

3.3 Verification

Suitable verification procedures are necessary to produce a final building which actually meet the contracted sound class (or any requirement). Traditionally, acousticians are involved at a late stage performing measurements in the building. This is too late if something is wrong, see Figure 1. If involved very late, the acoustician knowledge of the project is very limited which further complicate efficient measures. Undoubtedly, costs are minimized when the verification is carried out throughout the building process. As soon as decisions have been made or the work is already in progress, the verification should cover

- Requirement level, type of project contract, responsibility management
- Traffic density, type of traffic, sound pressure levels at the facade
- Structural framework, products in the building, final drawings
- Visits at the building site

- Measurements in the finalized building

Depending on each project, its location, its form for contract, the choice of structural material etc the need for verification within each part above vary and should be stated in the acoustic documentation.

The intention of this part of the handbook is to clarify the need for surveillance carried out continuously throughout the process, and not solely relying on acoustical measurements. Continuous visual inspections during the construction phase and documentation of products which form a part of the building is important in order to take actions if something appears to be wrong – correcting measures may then be carried out immediately.

Furthermore, during the building process current basic prerequisites for the design have to be laid down. One such issue is to define the traffic conditions (traffic density, number of heavy vehicles etc) in order to choose the right windows and façade. The handbook also contain information of security margins during design in order to manage the final requirements with sufficient probability, based on calculations which are compared to measurements presented in a Nordtest report NT Tec 603 [4] and a report from the Forum for building costs [5, 6].

4 CONCLUSIONS

There is a need for a shake-up regarding knowledge of aspects that cause acoustical problems in buildings. Every mistake not being corrected as early as possibly costs a lot of money and the final product quality may deteriorate more than necessary. A new Swedish handbook has been issued by our national authorities, to provide help to those who work in projects to secure the acoustical quality of buildings.

To promote acoustic knowledge directly to the building industry has become an even more important task during the last decade (or decades) since the teaching of building acoustics at the universities has been reduced. At the same time, modern buildings become more and more complicated, and the building acoustic demands from inhabitants are increasing. Lightweight structures (e.g. by wood or steel) are increasingly being used in multi storey residential buildings, which present huge future challenges to the industry and to the acousticians.

The handbook is presently available in Swedish only. However, some countries have shown interest to translate the handbook into their language and of course it would be interesting to publish it in other languages, primarily into English.

5 REFERENCES

[1] EN 12354 Building acoustics - Estimation of acoustic performance of building from the performance of elements. Parts 1-6. The parts 1-4 have been published by ISO without changes (ISO 15712 1-4)

[2] SS 25267 Acoustics - Sound classification of spaces in buildings - Dwellings

[3] SS 25268 Acoustics - Sound classification of spaces in buildings - Institutional premises, rooms for education, preschools and leisure-time centres, rooms for office work and hotels

[4] NT Tech 603, Simmons C., “Reproducibility of measurements with ISO 140 and calculations with EN 12354.” ISSN: 0283-7234. Nordic Innovation Centre, Oslo (2005), www.nordicinnovation.net/nordtest.cfm.

[5] National Board of Housing Building and Planning, “Bostäder och nya ljudkrav”. ISBN: 978-91-85751

[6] Hagberg K., Simmons C., “Consequences of new building regulations for modern apartment buildings in Sweden” *Proceedings of INTER-NOISE 06*, 2006. This paper gives is a brief summary of reference 5.

Paper VI

inter-noise 2004
Prague • Czech Republic • August 22–25

The 33rd International Congress and Exposition
on Noise Control Engineering

Reliable building element sound insulation data for EN 12354 calculations facilitates analysis of Swedish dwelling houses

C. Simmons

simmons akustik & utveckling ab, Krokslatts Fabriker 1, SE-431 37 Molndal, Sweden
christian.simmons@euromail.se

Abstract [48] This paper describes a practical procedure to build a structured database of sound insulation data, that describes the constructions typical for older dwelling houses. The data are mainly based on calculations, but efforts have been made to compare calculated results to measured, and to verify that the calculated data *in situ* according to EN 12354 are reasonably representative for the actual types of building. Feed back from the users of the database may support future analyses and updates of the database or the calculation model.

1 INTRODUCTION

In Sweden, modernization of old dwelling houses is an important and growing building activity, e.g. infill development, expansion of attic storeys and conversion of other types of building into dwellings. Initially, severe problems with annoyance among the habitants were caused by poor sound insulation in these new dwellings. As a consequence thereof, sound insulation is now assigned high priority during the planning process. New building codes, within the third edition of the Swedish standard on sound classification [1], explicitly advise that a building acoustic documentation should be presented at an early stage of a project, based on calculations or measurements. Measurements in the building are often required, but they can only confirm the actual conditions. To predict the acoustic performance of a renovated building, with major changes of construction undertaken, calls for theorethical calculations. These may be difficult to perform however, since there is a lack of reliable data on airborne and impact sound insulation of older building types. There is some empirical knowledge of typical acoustical problems within houses from the 1950-, -60 and -70 decades, but it is often not structured such that it can be readily applied to future projects. With pensioning of experienced acoustic engineers close at hand, there was an urgent need to document empirical and theorethical knowledge of building acoustic properties of construction typical of old houses. A survey has been undertaken among the experts, and some literature data were gathered as well. A database of sound insulation of typical constructions suitable for the calculation of sound insulation *in situ* according to the European standard EN 12354 [2] has been established, including data for suitable renovation measures. The constructions are structured in the database according to an architectural survey, where building types established during 1880-2000 have been described [3]. A structured approach to find consistent data for these constructions was established, as described below.

2 PROCEDURE

Several aspects were considered before the survey was started, on various techniques to establish data for the constructions.

Among acoustic engineers, measurements are often considered more reliable than theorethical calculations, in spite of the difficulties with interpretation due to the large scatter found in laboratory measurements as well as results from the field. There is an expressive saying that concludes the problem: “everybody trust results from measurements except those doing them, but no one believes in results from calculations except those performing them”. As is shown in the table below, all known methods to determine sound insulation data have benefits and disadvantages that had to be accounted for in this project.

Type of analysis	Advantages	Disadvantages
Laboratory measurements	High repeatability (within the same lab.) Describes the actual construction, as-is	Moderate reproducibility between labs Many constructions are not tested (high costs, no owner of the data) Idealized mounting conditions
Field measurements	Estimate performance of assembled constructions in the field as actually built Influence of room modes and structural loss factors included	Data valid for the test rooms only Mix of direct and flanking transmission Difficult to predict influence of changes Moderate repeatability of test results Many types of house not tested
Theorethical calculations	Virtually all types of construction may be analyzed Consistent estimate of performance with respect to mass, change of construction etc	Unknown precision (systematic errors) Does not describe real constructions (acoustic behaviour is idealized)

The choice of source for construction data is not obvious. The strategy chosen in this project was to try a combination of all methods. A calculation model was compared to measurements in several laboratories and a statistical correction was established for several categories of construction. Then, the input data of the actual constructions in the database were calculated theoretically and corrected according to the comparison with laboratory measurements. As a final step, comparisons of calculated sound insulation in buildings with field measurements were made. This procedure combines, to some extent, the consistency of calculated data with the legitimacy of measured data. The procedure is described in detail below.

2.1 Describing typical constructions of old houses

It is necessary to describe the constructions typical for old houses in a schematic and structured way. Otherwise, the amount of variations in construction and sound insulation data may be prohibitive for the purpose of establishing a database that is practical to use. Fortunately, an architectural survey had been undertaken in Sweden some years ago, and the constructions typical for each decade have been described and illustrated [3]. An example is given in Figure 1. The task of the project was then to assign acoustical properties to the constructions listed in this survey.

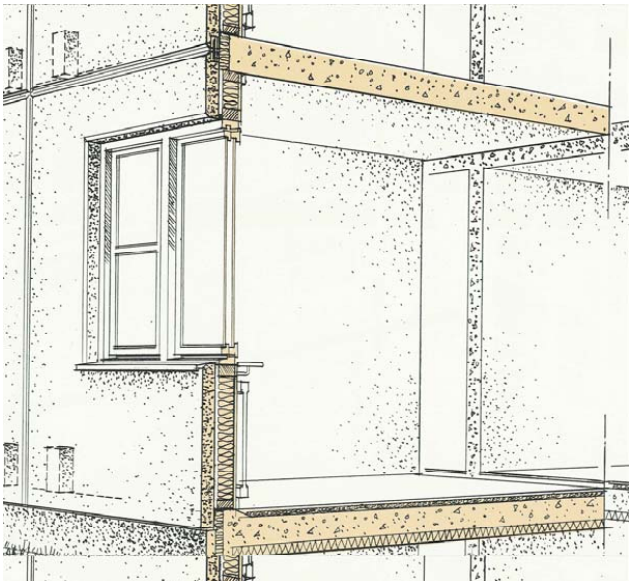


Figure 1. *A sample illustration of house construction typical for the 3-5 storey houses built in the 1950:s, cited from ref. 3. The parquet floor rests on 30 mm sand, which is replaced during renovation.*

2.2 Survey for measured data of old houses

The initial aim of the project was to document empirical experience of experts on building acoustics, who were asked to describe typical features of older houses from their own experience. Some field measurements were collected, that were thought to represent typical types of old building. However, only a few measurements from the same type of building were found. For many constructions, there were no data found at all. In most cases, the measurement reports were not completed with documentation on constructions of the measurement rooms. Therefore, it was uncertain which constructions they referred to. Another specific problem was the measurement uncertainty of 20-50 year old measurements and the limited frequency range (100-3150 Hz). In the Swedish building codes, a documentation is required in the range 50-3150 Hz.

The field measurement data were not used to describe single constructions, but will instead be applied at a later stage to verify results from calculations according to clause 2.5.

2.3 Comparison between measured data and calculated data

Measurement data from various laboratories were collected and compared to theorethical calculations, using the Insul software [4]. For each type of construction, the average difference between the calculated and the measured insulation was calculated as well as the standard deviation. An empirical correction to calculated results was then established for several types of construction, e.g. light weight inner walls and external walls, light weight concrete walls, windows and floorings.

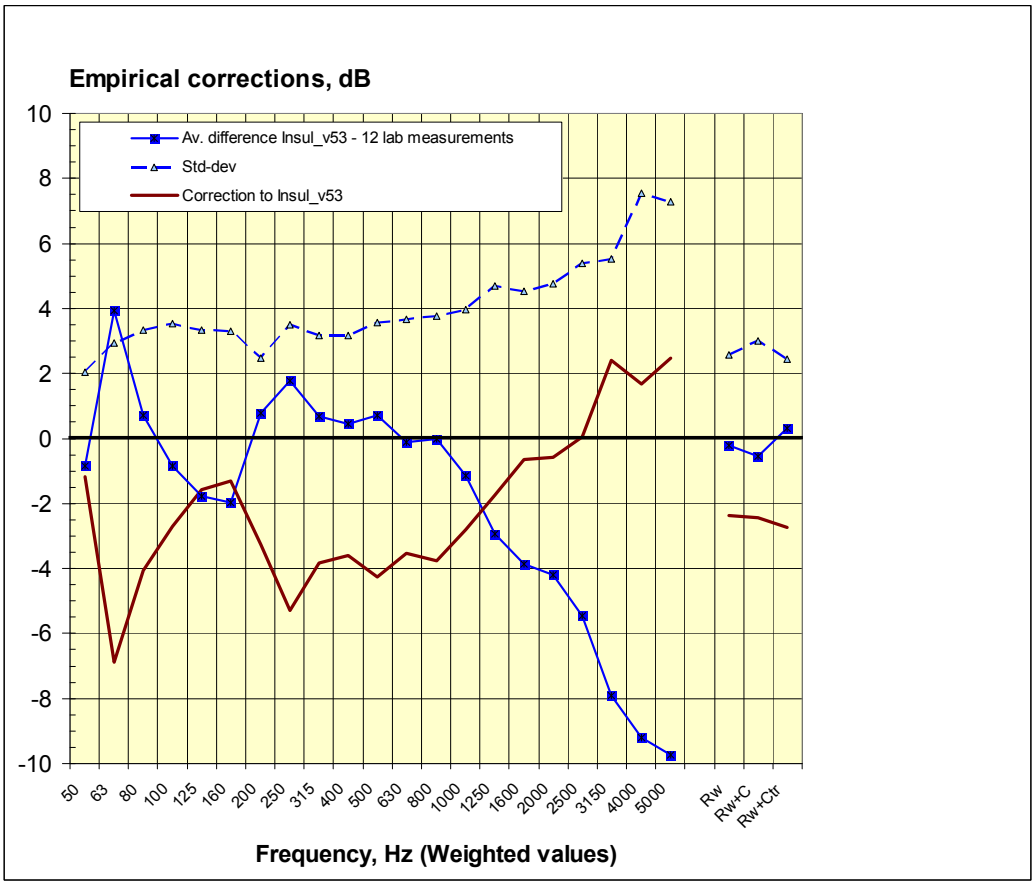


Figure 2. *Average and standard deviation between measured data and calculated data. Comparison of 12 light weight external walls with various types of insulation and cladding on wooden battens.*

2.4 Calculating and correcting input data for typical constructions

As a rule-of-thumb, one should keep a safety margin between sound insulation *in situ* calculated according to EN 12354 and a required value. This margin has to be defined by the client or the acoustic expert, but it should take into account uncertainty in the building element data, the accuracy of the calculation model and the uncertainty in field measurements. A margin of 3 dB is often advised. The choice of building element data should preferably be corrected for the uncertainty that pertains to the specific construction only, i.e. not correct for the general uncertainty. For instance, data of light weight constructions typically show a larger scatter than heavy constructions, and the safety margin may be chosen differently.

In the database, the correction of input data for light weight building elements were determined as the sum of the average deviation increased by one standard deviation, in third octave bands 50-5000 Hz. For heavy constructions, only the average deviation was used. As an exception to the procedure described, light weight timber joist floors were adopted from laboratory studies and corrected by -3 dB from empirical experience. The performance of these floors tend to be impressive in the laboratory but more moderate in the building. One reason for this difference may be flanking

transmission through the supporting studs and walls, which is not handled by the calculation model in EN 12354. Also, transmission losses at junctions between light weight constructions are not yet well understood, nor documented.

The input data of the constructions listed in [3] were then calculated, corrected and tabulated in the database. Schematic illustrations were made to show each type of construction.

2.5 Verifying data by comparing to other *in situ* measurements

About 30 field measurements will be analyzed in June 2004 and the results presented at the conference, where comparative calculations will be done according to EN 12354 parts 1 (airborne sound insulation) and part 2 (impact sound). The software for the calculations is BASTIAN version 2.1 [5]. The constructions of the actual building will be chosen from the previously established database. However, developing input data for heavy concrete slabs and walls is not a part of this project, they will be chosen according to a previous study and the annex B of EN 12354. In case large deviations are found, a more detailed study will be undertaken to explain the deviation and try to correct the input data accordingly.

3 EXAMPLES

Two types of construction required an extensive work to describe: timber joist floors and external timber stud walls with various types of cladding.

The acoustic performance of timber joist floors in situ and in the laboratory was analyzed by Bodlund [6]. Bodlund concluded, that a large scatter of data must be expected, even within the same building. Therefore, measurements should be taken in several rooms to document conditions before deciding upon measures to improve sound insulation.

Bodlund made some systematic studies in the laboratory at SP (The national testing and research institute). A reference timber joist floor was constructed, where various types of filling material, floorings and suspended ceilings were tested. The data from this study were incorporated in the database, together with results from two experimental studies on modern light weight timber joist floors [7], [8]. These measurement series give an impression on the efficiency of various renovation measures, but calculation results must be interpretated with great care when used to predict the performance of an actual construction, particularly if it is not well documented. Figure 3 shows some examples of slab tested in the laboratory.

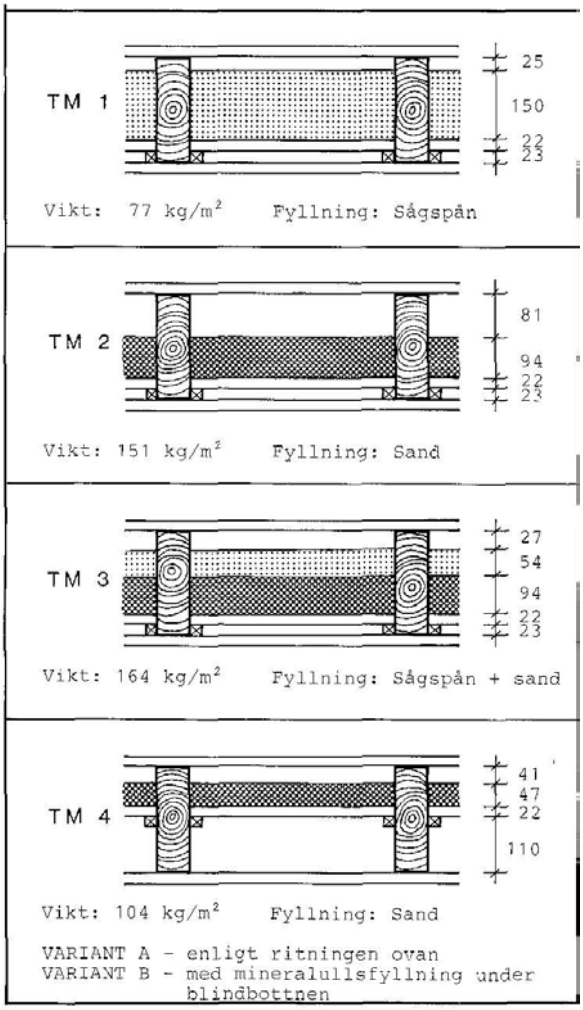


Figure 3. *Reference timber joist floor with various filling materials. "Sågspån" means sawdust, "vikt" means weight, "blindbotten" means blind floor. (From SP, ref 5)*

The external timber stud walls presented some difficulties with respect to variations in construction. Buildings from the 1930-1960 period have additional cladding (thermal insulation and a new panel). Several alternatives have been calculated according to the above procedure, but results from a large measurement series in the laboratory were also incorporated in the database. The user of the database may then choose a measured value when the construction fits the actual case, and then look at the calculated values to see what change can be expected in acoustic performance when additional layers are suggested.

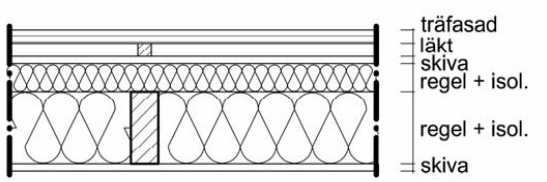


Figure 4. *Typical light weight timber stud exterior wall element, with new thermal insulation and panel added. "Regel" - stud, "skiva" -board, "läkt" -batten, "träfasad" -wooden cladding.*

4 CONCLUSION

A database of sound insulation data has been established, that describes the constructions typical for older Swedish dwelling houses in a structured way. The data are based on calculations, but efforts have been made to compare calculated results to measured, and to verify that the calculated data are representative for the actual constructions. The database presented is a first step towards a common set of reliable data for older buildings. However, feed back from the users of the database may call for adjustments of the data. Thus, the quality of the data in the database may be improved step by step, and there should be a dialogue between acoustic engineers using the data.

ACKNOWLEDGEMENTS

The concept of comparing field data with calculations was suggested by Dan B. Pedersen at Delta Acoustics & Vibration in Denmark. The support from the contractors NCC, JM and Skanska is greatfully acknowledged, as is the financial support from the Swedish building research fund SBUF.

REFERENCES

[1] SS 25267 Acoustics – Sound classification of spaces in buildings – Dwellings. Swedish Standards, www.sis.se.
[2] Building acoustics – Estimation of acoustic performance of buildings from the performance of elements – Part 1: Airborne sound insulation between rooms. Part 2: Impact sound insulation. CEN, www.cenorm.be
[3] L. Reppen *et al.* Så byggdes husen (*Constructions of old houses*). Report T1:1984, 5th edition. Formas publishers, Stockholm 2002. ISBN 91-540-5888-0. www.formas.se
[4] INSUL version 5.3. Marshall Day Acoustics New Zealand www.insul.co.nz.
[5] BASTIAN version 2.1. Datakustik GmbH Munich www.datakustik.de.
[6] K. Bodlund Brandmotstånd och ljudisolering i gamla hus med träbjälklag (*Fire resistance and sound insulation of old houses with timber joist floors*). ISBN 54049679. Formas publishers, Stockholm. Report T2:1989.
[7] Test results from SP, with permission from SNIRI/TMF (Nat. Assoc. of the Swedish Joinery Factories).
[8] L. Nilsson. Balkbjälklag i trä (*Timber joist floors*). Skanska Teknik/SBUF report 1033. www.sbuf.se

Paper VII

EURONOISE 2006
30 May - 1 June 2006 Tampere, Finland

VERIFICATION OF SOUND ABSORPTION REQUIREMENTS

Christian Simmons

simmons akustik & utveckling ab
Krokslätts Fabriker 1, SE-43137 Mölndal, Sweden
info@simmons.se, www.simmons.se

ABSTRACT

Measured reverberation times taken in 44 classrooms have been compared to values calculated according to the basic method of the new standard EN 12354-6. Both porous absorbers and perforated plasterboard absorbers were analyzed, since other studies have indicated they may behave quite differently *in situ* as compared to the laboratory. Systematic and random differences between the measured and calculated reverberation times have been calculated. From these differences, practical safety margins were derived, to be observed during design, when the type and amount of sound absorbers is estimated. The margin was calculated to a 90% certainty, that a measured reverberation time will not exceed the calculated value, provided that the type of room and furniture is of the same type as in the rooms used in the study. A special study in the laboratory will be presented at the conference.

1 INTRODUCTION

In a working draft of the second edition of SS 25268 (the Swedish standard for sound classification of common spaces, ref 1), requirements on room acoustical conditions have been suggested, where a calculated sound absorption area would be the main entity. In the current edition (1), reverberation times, as measured in the building (*in situ*), are specified for this purpose. Obviously, any type of requirement must be possible to handle during a design phase as well as to verify *in situ*. It is required by several parties, that both calculated and measured values must be in close agreement, at least on the average. Some scatter between calculated and measured data is inevitable, but the uncertainty of a calculation result as compared to a sample measurement should be possible to estimate (and correct for during design).

The strategy chosen was then:

- state an *estimated* reverberation time *in situ* for various types of space, as a design goal
- require the effective absorption area, types and amounts of absorber, shall be determined be the user
- input data shall be chosen, that make calculated values comply with measured, within a given uncertainty

The suggested method for calculation is the new standard EN 12354-6, completed during 2004 [2]. The type and amount of absorber is assumed to be specified in contracts etc, and constitute

the effective requirement. Verification of absorbers may then be done by a simple visual inspection, where prints on their back side is recommended. Measurements of reverberation time may still be used as a means of determining the amount of absorption in a space (furnished or unfurnished) before or after sound absorbers have been added, but measurements would no longer be the reference method (in case of dispute).

The method of calculation of the main section of EN 12354-6 is basically equivalent to the well known formula of Sabine, i.e. the sound fields are presupposed to be diffuse and the effective absorption area is expected to be independent of the location of the absorbers. However, there are some new concepts applied in EN 12354-6, for the estimation of the absorption of furniture and objects inside the space, which are based on their effective volume. These concepts are not as well examined, and it seemed appropriate to evaluate their influence on the calculated reverberation time by means of comparisons to field measurements. Furthermore, there are some field studies made, that indicate important discrepancies between calculated and measured reverberation times, that depend on type of absorber. These discrepancies constitute a trade barrier, which must be removed somehow.

In this paper, results are presented from a comparison made between 44 field measurements of reverberation times, taken mainly in classrooms and day-care centers, and the calculated values of each of these spaces. The measured data and room descriptions have been collected from acoustic consultants and manufacturers in the Nordic countries. The data cover both spaces with porous absorbers (mineral wool) and spaces with resonant absorbers (perforated gypsum boards, lined with a porous cloth). Sound absorption coefficients of acoustic tiles have been collected from the manufacturers catalogues. In some cases, the field case documentation has been vague and some generic data of absorbers and typical building materials have then been applied, according to common building practice.

2 BUILDING MATERIALS - SOUND ABSORPTION COEFFICIENTS

In order to enable calculations of the sound absorption and reverberation times of spaces without sound absorbing tiles, sound absorption coefficients of traditional building materials needed to be “standardized”. Data were collected from EN 12354-6 and a variety of publications and consultants. Some tables on absorption of building materials were established more than 40 years ago, and one cannot be fully confident in the validity of these data. Nevertheless, these type of tables are still widely used. By incorporating in the standard [1] a table of absorption coefficients of constructions and materials typical to our national building traditions, it is expected that these generic sound absorption coefficients will be widely used. Apparent discrepancies could be corrected in due time if several users report coherent observations to the Swedish standards committee. The values used in this study are collected in a “table 1”, which is omitted in this paper but presented in the project report [3].

In addition to the coefficients of materials, 8 types of furniture absorbers were calculated from their volume (according to ref. 1) and added to the table. These data represent the apparent sound absorption of desks, chairs, book shelves and other furniture. This absorption is not only related to porous materials, but as well the sound diffusing properties that reduce the reverberation time of a furnished space. At low frequencies, the absorption of small items was reduced, as well as the absorption of large items was increased if the item was assumed to have resonant surfaces (e.g. thin leaves or glazings).

3 COMPARISON OF CALCULATIONS WITH FIELD MEASUREMENTS

Differences between calculated reverberation times and measured have been evaluated for all spaces as well as for groups of spaces with similar types of absorber. In the latter case, spaces with two types of absorber were considered; porous absorbers (e.g. mineral wool) and resonant absorbers (e.g. perforated plaster boards with an air space behind). In each group, the mean and standard deviation between calculated and measured reverberation times have been calculated, as is illustrated by figures 1 and 2 below.

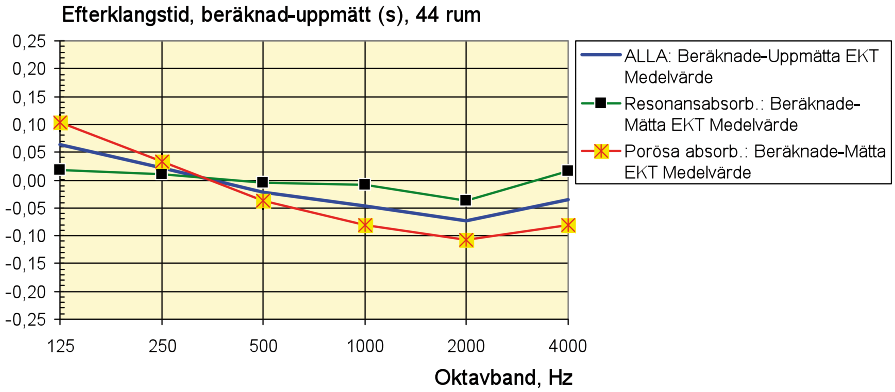


Fig. 1. Mean deviation between calculated and measured reverberation times, s. (44 spaces). Legend: "Efterklangstid"-reverberation time", "beräknad"-calculated, "uppmätt"-measured, "ALLA"-all 44 cases studied, "Resonansabsorb."-resonant tiles (21 cases), "Porösa absorb."-porous tiles (23 cases)

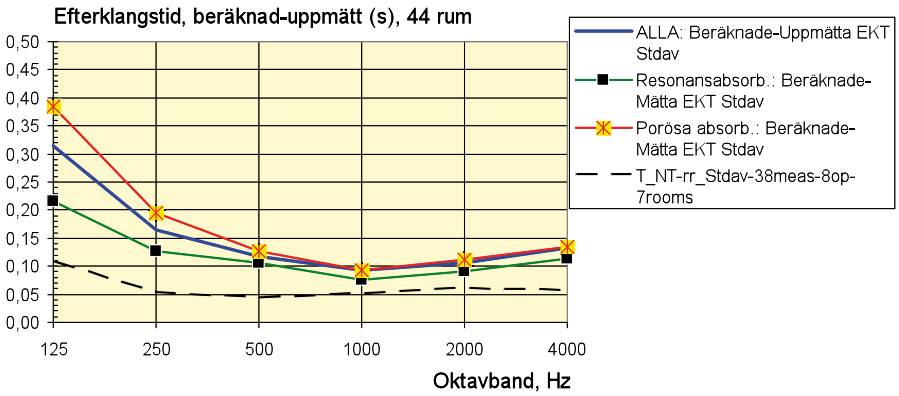


Fig. 2. Standard deviation between calculated and measured reverberation times, s. (44 spaces). Legend, see fig. 1. The line "T_NT-rr"-estimate of reproducibility of the measurement method [4].

The figure 2 shows the standard deviation of difference between calculated and measured reverberation times, in seconds. The dashed line "T_NT-rr_Stdav-38meas-8op-7rooms" line is an estimate of standard deviation of reproducibility of the measured reverberation time, taken from a Nordtest inter-laboratory study [4]. They were derived from 38 measurements, made by 8 operators in 7 different types of room. The comparison indicates that the differences obtained

can not be explained by measurement uncertainty only. However, the calculation method and the input data chosen do influence the differences obtained, c.f. the introduction.

The result of a calculation by EN 12354-6 with appropriate sound absorption coefficients may be corrected for the systematic and random differences given in figures 1-2. Thus, an appropriate safety margin may be established for each type of absorber. If this safety margin is applied, one may state which measured reverberation times *in situ* would comply (i.e. not exceed the calculated value), by a given probability. This probability was set to 90%. The systematic difference (mean deviation between calculated and measured reverberation times) is first subtracted from the calculated value. To correct for the scatter of data, the calculated value is also increased by the standard deviation multiplied by a statistical coverage factor of 1,28, which corresponds to a 90% probability of compliance with the required value, i.e. a 10% "risk". Fig. 3 shows the sum of negative mean deviation terms (fig. 1) increased by 1,28 times the standard deviation (fig. 2)

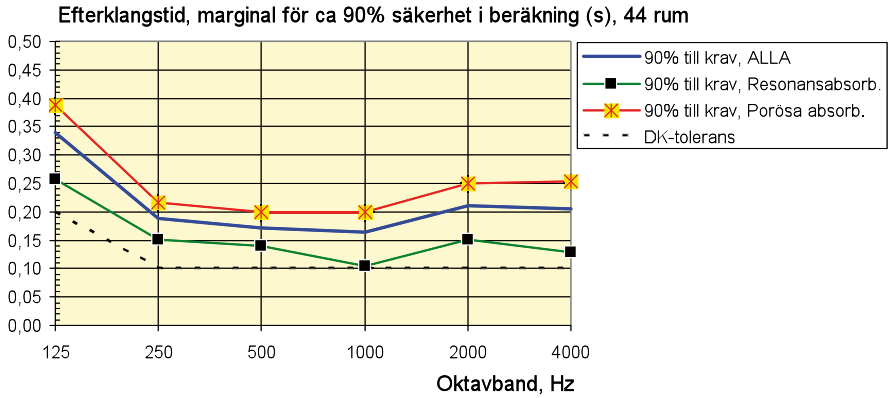


Fig. 3. Sum of negative mean deviation (fig. 1) and 1,28 times the standard deviation (fig. 2) between calculated and measured reverberation times, s. Legend, see fig. 1.

The dashed line shows a tolerance, proposed by Delta Akustik & Vibration to be included in the Danish regulations of working environments [Ehrvervs- och boligstyrelsen, ref. 5], that were suggested for the Swedish standard as well. Fig. 3 shows that even with these tolerances, sound absorbers must be designed to meet a shorter reverberation time, to ascertain measured values to comply, in case the diffusivity of the sound field can not be assessed.

The figures 1-3 are based on all cases studied (44). From these, 23 favourable cases were selected, which represent rooms with a large amount of sound diffusing furniture and room heights less than 3.1 m. The calculations were then repeated for these 23 favourable cases. Values of the negative mean term added to the term 1,28 times the standard deviation (corresponding to figure 3) are printed in figure 4.

The figure 4 indicates, that the tolerances prescribed in the Danish regulations correspond well to the practical results, in case the rooms have reasonably diffuse sound fields, i.e. contain diffusing furniture and a low room height. At high frequencies, resonant absorbers perform as expected and the margins could even be reduced somewhat. Porous absorbers tend to be overestimated by calculations at high frequencies.

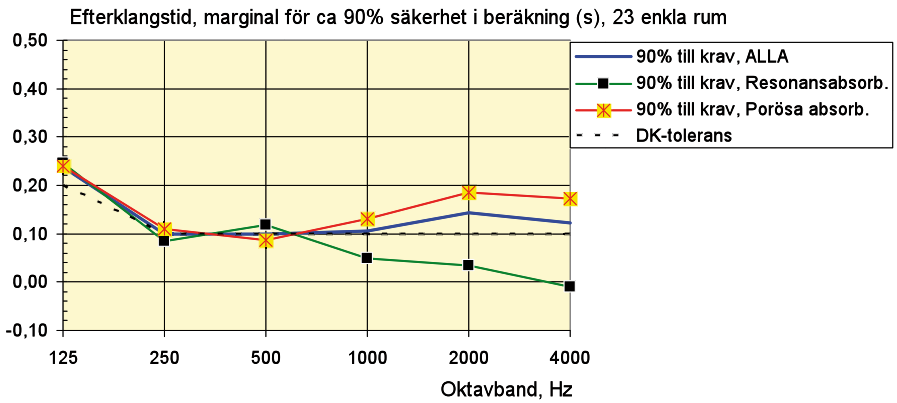


Fig. 4. Sum of negative mean deviation and 1,28 times the standard deviation between calculated and measured reverberation times, s. (23 cases). Legend, see fig. 1.

This difference is assumed to be explained by the measurement conditions in the laboratory according to ISO 354, where the laboratory is equipped with sound diffusors to make sound arrive at the absorbers from all angles. In typical classrooms, a larger proportion of sound tends to be incident at large angles or even be parallel to the absorber. Their sound absorption is then not as efficient. Resonant absorbers are less efficient and tend to function more equally in the laboratory as compare to the field.

4 SAFETY MARGINS

The results presented above confirm, that the calculation method in the European standard EN 12354-6 may give satisfactory results on the average. To obtain calculation results, that by a given probability (90%) would comply with measured values, some safety margins should be applied during design of absorbers for a specified space. Some margins are proposed, based on the figures 3 and 4, rounded to the nearest 0,05 seconds.

Table 1. Safety margins – rooms with limited sound diffusing properties:

Rooms with height >3,1m *or* inclined ceiling *or* less diffusing furniture on floor and walls:							
Safety margin for: Octave band	125	250	500	1000	2000	4000	Hz
Porous absorbers (mineral wool, wood fibre, textile materials)	0,20	0,10	0,10	0,10	0,15	0,15	sek
Resonance absorbers (perforated hard boards)	0,05	0,05	0,05	0,00	0,05	0,05	sek

Table 2. Safety margins – rooms with a favourable sound diffusing properties:

Rooms with rectangular shape *and* height <3,1m *and* diffusing furniture on floor and walls:							
Safety margin for: Octave band	125	250	500	1000	2000	4000	Hz
Porous absorbers (mineral wool, wood fibre, textile materials)	0,05	0,00	0,00	0,05	0,10	0,05	sek
Resonance absorbers (perforated hard boards)	0,05	0,00	0,00	-0,05	-0,05	-0,10	sek

The margins proposed should be sufficient to correct for both systematic and random variations between calculated and measured reverberation times in classrooms and similar types of space, provided the data for the sound absorbers have been determined correctly in the laboratory according to ISO 354. The uncertainty of compliance with a required value is less than 10%, if

a deviation of 0,2 sec at 125 Hz and 0,1 sec at frequencies 250-4000 Hz are accepted. These margins have been calculated based on data from rooms with approximately 0,6 seconds reverberation time. In other types of space, the margins may differ, but similar tendencies may be expected.

The tables 1-2 should be possible to use as generic data, where no other information exists. They may be replaced by other documentation in case the manufacturers can prove other data to be more representative for their products as applied to specific types of space.

5 LABORATORY TESTS IN A CLASSROOM, A WORK SPACE AND AN OFFICE

A special test facility has been established at the Swedish testing and research institute (SP, Borås), where an empty space 11,6m x 5,7m x 3,5m was equipped with furniture and sound absorbers in a variety of combinations. The aim was to test the efficiency of each absorber under field conditions in a classroom, a work space (half size) and an office (quarter size). The sound absorption of each set of absorbers was also determined in the reverberation chamber according to ISO 354. A summary of the results will be presented at the conference. Preliminary results show four important tendencies: 1) the measured reverberation time exceeds the calculated in all cases, 2) the influence of furniture was surprisingly high (which can not be explained only by the few porous parts of the chairs), 3) the difference in reverberation time between products based on mineral wool and plasterboard absorbers was almost negligible, 4) the strength of sound as well as the attenuation of sound with increasing distance hardly differed at all between different types of absorber (less than 1 dB, at high frequencies). This study indicates that most types of absorber work satisfactory in realistic rooms, independent of their absorption rating (EN ISO 11654).

REFERENCES

[1] SS 25268, working draft March 2005 (not published)

[2] EN 12354-6: Building acoustics - Estimation of acoustic performance of buildings from the performance of elements - Part 6: Sound absorption in enclosed spaces.

[3] Internal report SAU 2005135-1 to the SIS Tk197 committee. The report file (SIS-Tk197-SAURa-Dim-EN-12354-6.pdf, in Swedish) is available for download at www.simmons.se, link to “Böcker & Artiklar”.

[4] Simmons C. Reproducibility of measurements with ISO 140 and calculations with EN 12354. Report SAU NT-04030 (in English) to Nordisk InnovationsCenter (former NORDTEST). Download, c.f. [3]

[5] Lydforhold i undervisnings- og daginstitutionsbyggeri - Ajourføring af kravniveauet”. Erhvervs- og Boligstyrelsen, Februar 2003, www.ebst.dk

Paper VIII

Edinburgh, Scotland
EURONOISE 2009
October 26-28

Minimum area covered by a sound absorber estimated from its ISO 11654 classification and required reverberation time

Christian Simmons[a]
Simmons akustik & utveckling and Luleå University of Technology

ABSTRACT

The classification system according to the ISO 11654 standard[1] is frequently used in Sweden to prescribe an amount of sound absorption in common spaces. Typically, the minimum coverage of the ceiling is prescribed, where any sound absorber with the stated sound absorption class (A-D) is accepted. The coverage is often given as a percentage of the ceiling area, for its ease. However, there are evident risks that the resulting reverberation may differ considerably from the requirements when this apparently simple procedure is applied. Graphs and tables of this paper illustrate this problem. The ISO-classification would be more useful if it as well considered sound absorption at low frequencies (125 Hz) and narrowed the tolerances within each class. An alternative procedure is suggested, based on calculations of sound absorption and reverberation times in octave bands 125-4000 Hz according to EN 12354-6, that returns a table of specific products that fulfill all requirements.

1. INTRODUCTION

The Swedish sound classification standard SS 25268 states acoustic requirements on common spaces in buildings, such as classrooms, pre-schools premises, offices, hospitals and hotels. It expresses requirements on room acoustics by two means.

The quantitative requirement is the reverberation time *T*, from which an appropriate sound absorption area *A* shall be calculated according to the European standard EN 12354-6, with due respect to building materials and furniture. Whether the room boundaries are made from lightweight gypsum boards or heavy materials makes a substantial difference to the sound absorption at low frequencies and hence the need for additional absorption by e.g. an acoustic ceiling. Furniture increases diffusion at mid- and high frequencies, which may be considered as an extra amount of absorption in the room (if there are sound absorbing materials in the room). If so, the Sabine formula and the calculation scheme of EN 12354-6 return valid results, within acceptable tolerances[1]. The requirement includes a tolerance of 0,1 seconds in the range 250-4000 Hz and 0,2 seconds in the 125 Hz band.

The qualitative requirement of SS 25268 gives recommendations for the design of the room. In case of sparse furniture and parallel surfaces, the standard warns for excessive reverberation times and poor acoustics caused by flutter echoes. The standard advise the diffusion to be improved, or sound absorbers to be re-allocated to both ceiling and walls, rather than to increase the amount of sound absorption (or blame the products used for deficiency).

[a] info@simmons.se

In spite of these requirements, it is still frequent that requirements on sound absorption is stated only as a minimum “coverage factor”, expressed as a percentage (%) of the ceiling area, to be covered with any product with a stated sound absorption class A-D according to ISO 11654. In this paper, it is demonstrated some consequences that may follow from the large variance between products within the same sound absorption class.

In the last section of this paper, an improved procedure is suggested, to facilitate adequate design of sound absorption of common spaces, which consider natural absorption by materials and furnitures. The solutions fulfill requirements on reverberation times and give comfortable room acoustics for speech etc. A spreadsheet with data for a variety of sound absorbers and building materials is available for free download.1

2. COVERAGE OF CLASSIFIED SOUND ABSORBERS

In order to analyze how reverberation time requirements may be translated to a “coverage of a ceiling” with sound absorbers, a database of commercial sound absorbing products was established. Products from large manufacturers were entered to a database, e.g. from Danoline (Knauf Danogips), Ecophon (Saint Gobain), Parafon (Paroc), Roxull (Rockwool), Gyptone (Gyproc), Herakustik (Heraklith) and Träullit (Tepro). Both porous absorbers (mineral wool, wood fiber etc) and perforated hard absorbers (plasterboards) were analyzed. Each product may be entered at several distances from the slab floor, with sound absorption values taken from laboratory measurements accordingly. In all, about 500 combinations were included in the database.

The graphs and tables below show the coverage of all sound absorbers of the database, according to their measured sound absorption coefficients in octave bands as well as to their given sound absorption class according to ISO 11654. The coverage was calculated according to EN 12354-6, according to the expressions in clause 3. The room boundaries and furniture was assumed to contribute with a moderate “basic room sound absorption”, expressed in Table 1 as the coverage of the ceiling area (in percentage %).

Table 1: *Basic sound absorption of a common space with both lightweight and heavyweight materials as well as some furniture, typical for an office or a classroom.*

	Sound absorption area (m^2) per m^2 ceiling area					
Octave band [Hz]	125	250	500	1000	2000	4000
Room boundaries only	0,1	0,1	0,1	0,1	0,1	0,1
Room boundaries and furniture	0,2	0,25	0,25	0,25	0,25	0,25

As demonstrated in figure 1 below, the coverage may vary between 70% and 800% for products mounted close to the slab floor. The scatter of calculation results in figure 1 demonstrates the unpractical effect of allowing a large variance between products that belong to the same sound absorption class according to ISO 11654. For products mounted at 200 mm distance to the slab floor, the scatter of coverage within each class (on the right side of the figure) is reduced compared to the “thinner” solutions on the left side of the figure. This is explained by the increased sound absorption at low frequencies at 200 mm.

3. ACCURATE TABLES OF AMOUNT OF SOUND ABSORBERS

The building industry requested a simple design scheme (tables) for an appropriate selection of sound absorbers with respect to a reverberation time requirement, expressed by their sound absorption class (A-D) and coverage of the ceiling (%). In order to meet this request but still obey to the requirements in octave bands of SS 25268, both tables and an interactive spreadsheet1 were established.

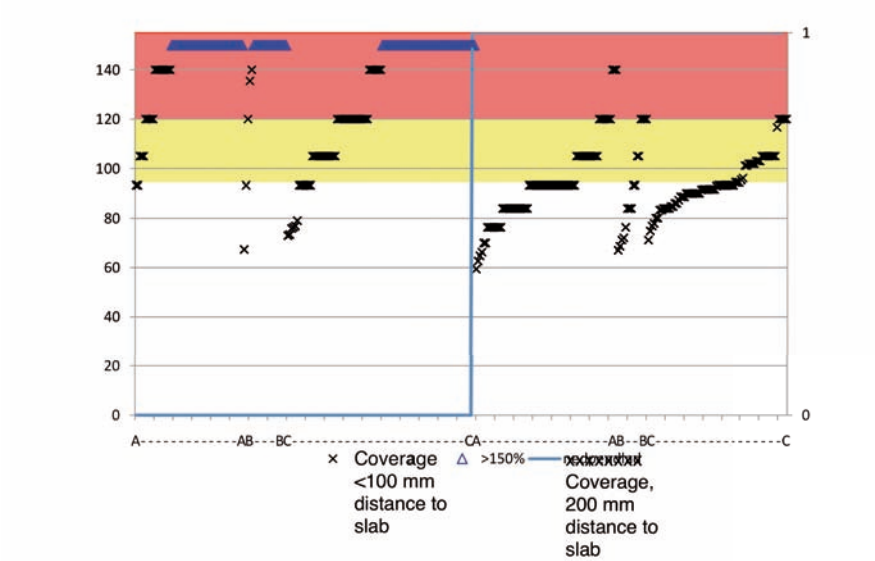


Figure 1: Minimum coverage (%) of a ceiling with 500 sound absorbers of class A, B or C according to ISO 11654. The requirement is in this case *T*=0,6 seconds 250-4000 Hz, 0,8 s at 125 Hz. Left part, absorbers class A, B and C mounted close to the slab (typically 20-50 mm). Right part, absorbers are mounted at 200 mm distance. Coverage factors larger than 150% are marked with a Δ-sign. Yellow field means that both ceiling and parts of the walls must be covered. Red means unfeasible application. The room is furnished with diffusing items. The ceiling height is 3,1 m.

The spreadsheet (cf section 5) calculates the amount of each absorber in the database, with respect to the boundaries of the room as well as the amount of furniture. The pre-set values are given in table 1. The spreadsheet was used to define tables that translate a reverberation time to the need for sound absorption under given prerequisites. The tables 2 and 3 give a broad overview of all products of the database. The tables 4 and 5 display a narrow selection of the best products within each class.

The requirements of SS 25268 are

1. The average reverberation time of the 250-4000 Hz octave bands must fulfill the required reverberation time *T*
2. Within one or more octave bands in this range, the result may deviate 0,1 second from *T*
3. Within the 125 Hz octave, the result may deviate 0,2 second from *T*

This means, the coverage factor of a sound absorber (*cf*) must be sufficient to fulfill

$$cf_{125} = [\frac{0{,}16 \times h}{T + 0{,}2} - \alpha_{room,125}] / \alpha_{absorber,125}$$ in the 125 Hz octave band (1)

$$cf_i = [\frac{0{,}16 \times h}{T + 0{,}1} - \alpha_{room,i}] / \alpha_{absorber,i}$$ in each octave band *i* 250-4000 Hz (2)

$$cf_{average} = [\frac{0{,}16 \times h \times 5}{T} - \sum_{250}^{4000} \alpha_{room}] / \sum_{250}^{4000} \alpha_{absorber}$$ average of octave bands 250-4000 Hz (3)

Table 2a: *Coverage of classified sound absorber vs. reverberation time of a furnished space. Intended for rooms without requirements at 125 Hz. Room absorption from Table 1, row 3*

For rooms with T+0,2 sec requirement at 125 Hz, the highest coverage of table 2a and 2b apply.		*Coverage of ceiling with sound absorbers (% of ceiling area), with products of class A-C (ISO 11654)*					
		A		***B***		***C***	
Available products that fulfill T req (%):		*10 perc*	*90perc*	*10 perc*	*90perc*	*10 perc*	*90perc*
Reverberation time T (s)	*Typical absorption* / *Room height (m)*	*0,85*	*0,6*	*0,70*	*0,5*	*0,65*	*0,4*
0,4	2,7	72%	102%	88%	123%	94%	154%
	3,1	87%	124%	106%	148%	114%	186%
	3,5	102%	145%	124%	174%	134%	218%
0,5	2,7	55%	78%	67%	94%	72%	118%
	3,1	68%	96%	82%	115%	89%	144%
	3,5	80%	114%	98%	137%	105%	171%
0,6	2,7	43%	61%	52%	73%	56%	92%
	3,1	54%	76%	66%	92%	71%	115%
	3,5	65%	92%	79%	110%	85%	138%
0,8	2,7	27%	38%	33%	46%	35%	58%
	3,1	35%	50%	43%	60%	46%	75%
	3,5	44%	62%	53%	74%	57%	93%
1,0	2,7	17%	24%	20%	29%	22%	36%
	3,1	24%	33%	29%	40%	31%	50%
	3,5	30%	43%	37%	52%	40%	65%
1,2	2,7	10%	14%	12%	16%	13%	21%
	3,1	15%	22%	19%	26%	20%	33%
	3,5	21%	30%	26%	36%	28%	45%
	4	29%	40%	35%	48%	37%	61%
1,5	2,7	2%	3%	3%	4%	3%	5%
	3,1	7%	10%	9%	12%	9%	15%
	3,5	12%	17%	14%	20%	15%	25%
	4	18%	25%	21%	30%	23%	38%

The third row of tables 2a and 2b estimates the availability of commercial sound absorbers of the database that may fulfill the requirement when covering the ceiling as listed in its left hand column. 10% of the database within a sound absorption class typically means that 1-3 products from at least 2 manufacturers fulfill the T-requirement. 90% means that most products of this class would fulfill the requirement if they cover the larger area listed in the right hand column.

The typical absorption value stated in table 2a is predominantly from the 250 Hz octave band when the product belongs to class A or B. For the C-classified products, other octave bands may determine the class and the coverage needed.

Since the rules of ISO 11654 do not consider the 125 Hz octave band, it was necessary to look into the sound absorption at this band and calculate the coverage needed. The results are given in table 2. Some plasterboard products with a large empty space to the slab floor (*plenum*) might have good sound absorption at low frequencies but need additional absorption at high frequencies to meet all requirements. For these products, table 1 may be used to determine the coverage. Other products may have high sound absorption in the range 500-4000 Hz, but less absorption at 125 and 250 Hz, typical for thin mineral wool absorbers. For these products, the required coverage according to table 2 is considerably stricter than table 1. Hence, both tables must be used to find an appropriate coverage.

The ISO-classification would be more useful if it as well considered sound absorption at low frequencies (125 Hz) and narrowed the tolerances within each class.

Table 2b: *Additional requirement for furnished rooms with requirements at the 125 Hz octave band.*

Sound absorption @125 Hz		<0,15	0,2	0,3	0,4	0,5	0,6	0,7	0,8
Class A-C from ISO 11654 % of products fulfilling T+0,2s		A, B, C (90%)				A, B (10%)	C (10%)		
Reverberation time T (s)	*Room height (m)*								
	2,7	347	260	173	130	104	87	74	65
0,4	3,1	418	313	209	157	125	104	90	78
	3,5	489	367	244	183	147	122	105	92
	2,7	278	209	139	104	83	70	60	52
0,5	3,1	339	254	170	127	102	85	73	64
	3,5	400	300	200	150	120	100	86	75
	2,7	227	170	113	85	68	57	49	43
0,6	3,1	280	210	140	105	84	70	60	53
	3,5	333	250	167	125	100	83	71	63
	2,7	155	116	77	58	46	39	33	29
0,8	3,1	197	148	99	74	59	49	42	37
	3,5	240	180	120	90	72	60	51	45
	2,7	107	80	53	40	32	27	23	20
1,0	3,1	142	107	71	53	43	36	30	27
	3,5	178	133	89	67	53	44	38	33
	2,7	72	54	36	27	22	18	16	14
1,2	3,1	103	77	51	39	31	26	22	19
	3,5	133	100	67	50	40	33	29	25
	4	171	129	86	64	51	43	37	32
	2,7	36	27	18	14	11	9	8	7
1,5	3,1	61	46	31	23	18	15	13	11
	3,5	86	65	43	32	26	22	18	16
	4	118	88	59	44	35	29	25	22

4. TABLES OF COVERAGE WITH THE BEST ABSORBERS

The tables 2a and 2b may be too complex for practical applications, and an attempt was made to establish simpler tables. The tables 3a and 3b display coverage of sound absorbers for each class as in tables 2, but only the best products within each sound absorption class were used to determine the coverage. Clearly, the recommended coverage then applies only to this selection of products and not to all products of a given sound class. This has to be stated in architectural prescriptions etcetera.

At the right hand column of table 3a, the minimum absorption factor at 125 Hz is tabulated, assuming 100% coverage of the ceiling.

5. SPREADSHEET WITH COVERAGE FOR EACH ABSORBER

It was made clear during the calculation work, that the large variance of sound absorption within each class makes it difficult to state a functional requirement that leaves the choice of product open and yet secures an appropriate amount of sound absorption to meet the required reverberation time. The database of sound absorbers and the calculation expressions (1-3) were therefore made accessible for anybody to download. The intention is that the architect or the acoustic consultant enters the appropriate data for the room boundaries and the furniture, or at least some assumed properties that fit the intended use of each type of room. This applies to classrooms, offices, hospital premises etcetera.

Table 3a (top) and 3b (bottom).
Coverage of selected (best) products from each class A-C, at two mounting distances.
Top: with requirements at 125 Hz, in furnished rooms.
Bottom: Without requirements at 125 Hz, in furnished or unfurnished rooms.

		Best products, in furnished rooms, incl. requirements at 125 Hz						*Cover. 100%*
Rev.time T_{20}	*Room height* *h*	*Suspended min 200 mm* *A*	*B*	*C*	*Suspended <100 mm* *A*	*B*	*C*	*=> min. abs @ 125 Hz*
0,4s	2,7m	95%	110%	115%	130%	150%	120%	0,55
	3,1m	115%	130%	140%	160%	180%	140%	0,65
	3,5m	135%	155%	160%	180%	210%	170%	0,75
0,5s	2,7m	75%	85%	90%	105%	120%	95%	0,45
	3,1m	90%	100%	110%	125%	145%	115%	0,55
	3,5m	110%	120%	130%	150%	170%	135%	0,6
0,6s	2,7m	60%	70%	70%	85%	95%	75%	0,35
	3,1m	75%	85%	85%	105%	120%	95%	0,45
	3,5m	90%	100%	100%	125%	145%	110%	0,5
0,8s	2,7m	40%	45%	45%	60%	65%	50%	0,25
	3,1m	55%	60%	60%	75%	85%	65%	0,3
	3,5m	65%	70%	70%	90%	105%	80%	0,4

		Best products, with/without furniture, no requirement at 125 Hz					
Rev.time T_{20}	*Room height* *h*	*Furnished rooms* *A*	*B*	*C*	*Unfurnished rooms* *A*	*B*	*C*
0,4s	2,7m	85%	100%	105%	100%	125%	125%
	3,1m	105%	120%	125%	120%	150%	145%
	3,5m	120%	140%	145%	135%	170%	165%
0,5s	2,7m	65%	75%	80%	80%	95%	95%
	3,1m	75%	90%	95%	95%	110%	115%
	3,5m	90%	105%	110%	105%	130%	130%
0,6s	2,7m	50%	55%	60%	65%	80%	80%
	3,1m	60%	70%	75%	75%	95%	95%
	3,5m	70%	85%	85%	85%	110%	110%
0,8s	2,7m	30%	35%	35%	45%	60%	60%
	3,1m	40%	45%	45%	55%	70%	70%
	3,5m	45%	55%	55%	65%	80%	80%
1,0s	2,7m	20%	25%	25%	35%	45%	45%
	3,1m	25%	30%	30%	40%	55%	55%
	3,5m	30%	40%	40%	50%	65%	65%

The figure 2 illustrates the result of such a choice, and some sample products that may then be appropriate. The spreadsheet may be sorted with respect to coverage, mounting distance, manufacturer etcetera. Instead of prescribing a coverage with a given sound absorption class, the specification is based on a reverberation time and a few examples of feasible products that meet the requirements. Whenever alternative solutions are considered, they may easily be compared on exactly the same premises as the original solutions. This means that optimal sound absorbing solutions may be chosen for the all types of room condition. The design of furniture, diffusion etcetera should also be described clearly, to improve speech intelligibility and avoid problems, e.g. flutter echoes.

Figure 2: Minimum coverage (%) of a ceiling with specific sound absorbers, based on their sound absorption in octave bands according to ISO 354 (lower part of the table). The requirement is in this case chosen to *T*=0,6 seconds 250-4000 Hz, 0,8 s at 125 Hz. Left column displays the coverage. Right column show the sound absorption class according to ISO 11654. The room is furnished with diffusing items, room absorption specified in row 4. The ceiling height is 3,1 m, specified to the right.

SS 25268	Octave band, Hz						
Tabulated T (s)	125	250	500	1000	2000	4000	**Room Height**
0,6	0,8	0,7	0,7	0,7	0,7	0,7	**3,1**
Room absorp:	**0,20**	**0,24**	**0,26**	**0,27**	**0,27**	**0,30**	

Coverage(%)	125	250	500	1000	2000	4000	AritmAverage
125-4000 Hz	Coverage (%) calculated for each octave band 125-4000 Hz and for the aritmethic average:						
87	0,64	0,72	0,64	0,67	0,72	0,68	0,87
84	0,64	0,63	0,64	0,67	0,72	0,68	0,84
88	0,75	0,67	0,69	0,67	0,67	0,81	0,88
69	0,69	0,67	0,53	0,49	0,43	0,41	0,63
57	0,49	0,49	0,47	0,44	0,43	0,43	0,57
88	0,83	0,85	0,69	0,58	0,62	0,81	0,88
85	0,83	0,85	0,69	0,58	0,58	0,58	0,82
91	0,83	0,78	0,69	0,73	0,72	0,68	0,91
69	0,55	0,59	0,47	0,46	0,62	0,62	0,69
90	0,64	0,49	0,50	0,55	0,67	0,90	0,74
61	0,59	0,52	0,50	0,49	0,48	0,41	0,61
58	0,52	0,52	0,50	0,44	0,43	0,41	0,58
69	0,69	0,47	0,45	0,44	0,43	0,41	0,56
65	0,64	0,47	0,50	0,55	0,62	0,45	0,65

Product	Sound absorption coefficients (m2 absorption area per m2 product area)						Sound
Tillverkare, produkt, tjocklek, total-	125	250	500	1000	2000	4000	class A-C
Danoline Designpanel 1200 M2F -	0,65	0,65	0,7	0,65	0,6	0,6	C
Danoline Q1 + 200 mm mineralull	0,65	0,75	0,7	0,65	0,6	0,6	C
Danoline Q1, nedp 500 mm (t=13,	0,55	0,7	0,65	0,65	0,65	0,5	C
Ecophon Focus F on secondary sp	0,6	0,7	0,85	0,9	1	1	A
Ecophon Master A/alpha + Master	0,85	0,95	0,95	1	1	0,95	A
Ecophon Master C/beta tkh = 200	0,5	0,55	0,65	0,75	0,7	0,5	C
Gyptone BIG Sixto 65 -300 mm su	0,5	0,55	0,65	0,75	0,75	0,7	C
Gyptone Line 04-suspended 200 r	0,5	0,6	0,65	0,6	0,6	0,6	C
Gyptone Quattro 20 - 50 mm min.,	0,75	0,8	0,95	0,95	0,7	0,65	C
Gyptone Rigitone 10/23-200 mm s	0,65	0,95	0,9	0,8	0,65	0,45	C
Herakustik Herakustik® star 35 mm	0,70	0,90	0,90	0,90	0,90	1,00	A
Parafon Bullerskiva 1379 50 tkh =	0,8	0,9	0,9	1	1	1	A
Roxull Polaris (t=40, tkh=200)	0,6	1	1	1	1	1	A
Träullit 25 mm TRÄULLIT with 45	0,65	1	0,9	0,8	0,7	0,9	B

6. CONCLUSIONS

It has been demonstrated that the large variance of sound absorption accepted within the limits for each sound absorption class according to ISO 11654 makes the classification system less practical. The idea is to state a functional requirement (sound absorption class) that leaves the choice of product open and yet secures an appropriate amount of sound absorption to meet the required reverberation time. However, it is safer and more economical to calculate the amount of specific products according to EN 12354-6, with respect to the boundaries and furniture. A database of sound absorbers and the calculation expressions (1-3) are accessible for anybody to download.[2] This allows the architect or the acoustic consultant to enter appropriate data for the building materials and the furniture, and choose among a variety of products, with the appropriate coverage tabulated. This design procedure is applicable to classrooms, offices, hospital premises and similar.

ACKNOWLEDGMENTS

We gratefully acknowledge Erik Ipsen and Knauf Danogips (Danoline) for their support to this work, as well as Bo Gärdhagen at Gärdhagen Akustik for valuable contributions.

REFERENCES

1. European and International standards referred to in this paper are available through http://www.cen.eu/ and www.iso.ch, or any national standardization body.
2. Verification of sound absorption requirements. Simmons C. Euronoise 2006, Tampere Finland. A more extensive report in Swedish is available for download as PDF: http://www.simmons.se/redigerbart/SIS-Tk197-Dimens-EN12354-6.pdf.
   At this site, the spreadsheet (MS Excel 2003, in Swedish) is also available: http://www.simmons.se/Berakning-grundabs-ljudabs_SAU-GA_2009-04-05.xls