
**Acoustics — Measurement of sound
insulation in buildings and of building
elements —**

**Part 13:
Guidelines**

*Acoustique — Mesurage de l'isolement acoustique des immeubles et des
éléments de construction —*

Partie 13: Lignes directrices



Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

- type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;
- type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;
- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard ("state of the art", for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 140-13, which is a Technical Report of type 3, was prepared by Technical Committee ISO/TC 43, *Acoustics*, Subcommittee SC 2, *Building acoustics*.

ISO 140 consists of the following parts, under the general title *Acoustics — Measurement of sound insulation in buildings and of building elements*:

- *Part 1: Requirements for laboratory test facilities with suppressed flanking transmission*
- *Part 2: Determination, verification and application of precision data*
- *Part 3: Laboratory measurements of airborne sound insulation of building elements*
- *Part 4: Field measurements of airborne sound insulation between rooms*
- *Part 5: Field measurements of airborne sound insulation of façade elements and façades*

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- *Part 6: Laboratory measurements of impact sound insulation of floors*
- *Part 7: Field measurements of impact sound insulation of floors*
- *Part 8: Laboratory measurements of the reduction of transmitted impact noise by floor coverings on a solid standard floor*
- *Part 9: Laboratory measurement of room-to-room airborne sound insulation of a suspended ceiling with a plenum above it*
- *Part 10: Laboratory measurement of airborne sound insulation of small building elements*
- *Part 11: Measurement of impact sound improvement of light-weight floors*
- *Part 12: Laboratory measurement of room-to-room airborne and impact sound insulation of an access floor*
- *Part 13: Guidelines*

Introduction

This Technical Report is identical with Nordtest Technical Report NT TECHN REPORT 203, *Measurements of the acoustical properties of buildings — Additional guidelines* (approved 1992-11), which is the result of a Nordtest-financed project carried out by a Nordic project group.

The reason for publishing the Nordtest Report as an ISO Technical Report is to spread the report widely, in order to gain as much experience as possible before considering implementation of the guidelines in existing standards.

Acoustics — Measurement of sound insulation in buildings and of building elements —

Part 13: Guidelines

1 Scope

This part of ISO 140 gives guidelines on building acoustical field measurements, based on ISO 140 parts 4 and 7.

2 Guidelines

Guidelines are given in Nordtest Technical Report NT TECHN REPORT 203, *Measurements of the acoustical properties of buildings — Additional guidelines*, 1992, which is adopted as ISO/TR 140-13.

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NT TECHN REPORT 203

Approved 1992-11

**MEASUREMENTS OF THE ACOUSTICAL PROPERTIES
OF BUILDINGS — ADDITIONAL GUIDELINES**

Henrik S. Olesen

NORDTEST

TASKS

The tasks of Nordtest are to promote the safety of life, health, environment and material values, and to encourage the free exchange of trade. The approach adopted by Nordtest to achieve these objectives is:

- to develop, adopt and recommend test methods and to promote the use of these by industry and the authorities, and also in standardisation work
- to obtain international recognition of test results and the competence of the Nordic countries, for instance by quality assurance and verification of testing activity
- to endeavour to ensure that tests and the approval of test results are made in a resource and cost effective manner
- to promote the technical testing infrastructure in the Nordic countries by means of research, development of competence and collaboration, and
- to participate in the European and international development of testing and to promote Nordic interests.

ORGANISATION

The organisation of Nordtest consists of a board, a secretariat and nine technical groups. These groups are Acoustics and Noise, Building, Electronics, Environment, Fire, Mechanical Building Services (VVS), Mechanics, Polymers and Quality Assurance.

The work is directed by the Board which comprises representatives of all the Nordic countries. The members are appointed by the government or appropriate department of the country concerned.

The technical groups initiate and evaluate projects. The projects are often structured in such a way that they can be used as catalysts for the development of the combined technical competence in the Nordic countries. At present, about 250 Nordic projects are being carried out in some 40 firms and institutions.

The board and the technical groups are assisted by the secretariat which is responsible for day to day activity. The secretariat is located at Espoo, Finland.

FINANCIAL FRAMEWORK

The cost of the Nordtest secretariat and a large proportion of project activity is financed from the budget of the Nordic Council of Ministers. The grant for 1992 is approx 1,5 millions ECU. The work of the board and the technical groups is financed by the participating organisations.

PUBLICATIONS

Nordtest publishes test methods, technical reports and a register of test methods and technical reports.

NT TECHN REPORT 203

Approved 1992-11

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FOREWORD

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1. SUMMARY

Requirements of the acoustical quality of buildings are normally stated in the building code regulations of the individual countries. The building code regulations normally prescribe minimum requirements concerning airborne sound insulation, impact sound insulation, reverberation time and noise from technical installations.

Basic methods for measuring these quantities are given in international standards and Nordtest Methods. However, acoustical measurements in buildings are quite complicated, especially regarding airborne and impact sound insulation. The standards presume ideal acoustical behaviour of the rooms, which is in practical measurement situations almost impossible to achieve.

The standards prescribe the principles of the measurements, but often they give only little detailed information on how to establish a suitable measurement set-up in rooms differing from simple box-shaped rooms of normal living room size.

Often in field situations it can be very difficult to choose an optimal measurement set-up. On this background the purpose of this project is to prepare additional guidelines to be used together with the basic standards. The guidelines include proposals for suitable measurement set-ups in typical as well as atypical rooms.

The guidelines have been prepared partly based on theoretical consideration and experimental results and partly on practical experience from performing a great number of field measurements. A detailed experimental evaluation of the guidelines would be very comprehensive and would also widely exceed the limits of this project. Therefore, the proposed guidelines should not be regarded as recommendations at the same level of try out as the basic standards.

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2. INTRODUCTION

2.1. BACKGROUND

Verification of the internal acoustical quality of buildings typically comprises measurement of the following quantities:

1. Airborne sound insulation
2. Impact sound insulation
3. Reverberation time
4. Noise from technical installations

(Measurements of noise from the outside transmitted into the building are not included in the scope of this project.)

In the Nordic countries methods for measurement of airborne and impact sound insulation is basically performed according to the international standards ISO 140 Part 4 and 7, respectively. Regarding methods for measurements of reverberation time in rooms for normal use and noise from technical installations no suitable international standards exist at present. Measurements of reverberation time and noise from technical installations are carried out in accordance with procedures prescribed in the individual building code regulations. These procedures are usually based on the Nordtest Methods NT ACOU 053 concerning reverberation time and NT ACOU 042 concerning noise measurements or alternatively the international standards ISO 3382 and ISO/R 1996.

In Norway and Sweden additional standards have been worked out giving some instructions and modifications in relation to the basic standards (ref. [15], [16],[17]).

Especially for measurements of airborne and impact sound insulation it can often be very difficult to choose a suitable measurement set-up in atypical rooms exclusively based on the test procedures prescribed in the basic standards.

To improve the reproducibility of building acoustic field measurements there is a need for additional guidelines to be used together with the basic standards.

2.2. OBJECTIVE

The objective of this project is to prepare additional guidelines to basic standards for building acoustic field measurements.

The use of the guidelines should contribute to improvement of the reproducibility of building acoustic field measurements and furthermore, hopefully, facilitate the performance of measurements by avoiding time consuming consideration in actual measurement situations.

2.3. APPROACH

As mentioned detailed theoretical and experimental investigations covering the measurements dealt with in this project would be very comprehensive and would widely exceed the limits of the project. Therefore the guidelines have been prepared based on simple theoretical consideration, some experimental results and experience from a great number of field measurements.

The requirements of airborne and impact sound insulation in building code regulations are usually stated in form of the single number values R'_w and $L'_{n,w}$. These quantities are calculated from the sound reduction index determined for 1/3 octave bands in the frequency range 100-3150 Hz. It has been decided to work out the guidelines with the purpose of improving the accuracy of the determination of the sound reduction indices. The single number values have not directly been taken into consideration.

The proposed guidelines are primarily applicable for measurements in rooms in dwellings, schools, hotels etc. with volumes less than approximately 250 m³.

The basic idea of the guidelines is that examples of suitable measurement set-ups in typical as well as atypical rooms are shown on diagrammatic sketches. For actual measurement situations not directly covered by the examples it should be possible to derive a suitable set-up from the examples given.

It shall be stressed that the proposed additional guidelines are not recommendations at the same level of try out as the basic standards.

3. BASIC STANDARDS

The standards related directly to the guidelines are:

ISO 140, Part 4: Acoustics - Measurement of sound insulation in buildings and of building elements. Field measurements of airborne sound insulation between rooms.

ISO 140, Part 7: Acoustics - Measurement of sound insulation in buildings and of building elements. Field measurement of impact sound insulation of floors.

Note - ISO 140 Part 4 and 7 are for the time being under revision. In this project the committee drafts of 5. May 1992 have been used. In all probability the standards will be approved in the present form within a short time.

Nordtest Method NT ACOU 042, Rooms: noise level (Approved 1983-09).

Nordtest Method NT ACOU 053, Rooms: reverberation time. (Approved 1986-02).

Nordtest Method NT ACOU 069, Doors in buildings: airborne sound insulation. (Approved 1988-09).

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4. AIRBORNE SOUND INSULATION

4.1. INTRODUCTION

A measurement of the airborne sound insulation (sound reduction index) includes determination of the space and time average sound pressure level in the source room and the receiving room respectively, and the space average reverberation time in the receiving room.

The sound reduction index is given by

$$\begin{aligned} R &= L_1 - L_2 + 10 \log \frac{S}{A} \text{ [dB]} \\ A &= 0.163 \cdot \frac{V}{T} \text{ [m}^2\text{]} \end{aligned} \quad (4.1)$$

where

L_1	=	sound pressure level in the source room [dB]
L_2	=	sound pressure level in the receiving room [dB]
S	=	area of the test object [m ²]
A	=	equivalent absorption area of the receiving room [m ²]
V	=	volume of the receiving room [m ³]
T	=	reverberation time of the receiving room [s]

If the individual sources of errors are assumed to be uncorrelated, the normalized variance of the sound reduction index can be estimated from

$$\varepsilon^2(R) = \varepsilon^2(L_1) + \varepsilon^2(L_2) + \varepsilon^2(T) \quad (4.2)$$

where $\varepsilon^2(L_1)$ = normalized variance of the average sound pressure in the source room

$\varepsilon^2(L_2)$ = normalized variance of the average sound pressure in the receiving room

$\varepsilon^2(T)$ = normalized variance of the average reverberation time

Determination of the sound reduction index according to equation 4.1 assumes diffuse sound fields in the source and receiving room, respectively. In empty rooms with normal living room size the sound field will normally be approximately diffuse apart from the lowest measurement frequencies observed. Serious problems with non-diffuse sound fields especially occur in very small rooms - e.g. bath rooms - and in large rooms with a short reverberation time.

Detailed knowledge of the influence on the measurement accuracy of the room volume, reverberation time, number of loudspeaker and microphone positions etc. is an important basis for preparation of additional guidelines to ISO 140 Part 4.

In the following chapters 4.2-4.11 calculations and consideration concerning the accuracy of measurements of airborne sound insulation in different types of rooms are presented. Chapter 4.12 is a summary of ISO 140 Part 4. Based on the chapters 4.2-4.11 principle aspects regarding additional guidelines are considered in chapter 4.13. A proposal for additional guidelines is presented in chapter 4.14.

When possible, measurements and calculations have been carried out in the frequency range 50-5000 Hz. In cases where the frequencies 50-80 Hz and 4000-5000 Hz have not been included this is due to either a lack of data, because measurement results from former investigations not performed in the extended frequency range have been used, or because the theories used in the calculations are not valid at low frequencies.

Standard deviations presented in this chapter calculated from measurement results are determined as the sample standard deviation.

4.2. STATISTICAL ROOM ACOUSTICS

This chapter deals with statistical consideration concerning random errors of the determination of the average sound pressure level in a room. The calculations in this chapter are mainly based on theories from the references [1], [2] and [3].

4.2.1. Schröder cut-off frequency

Statistical consideration on the sound field in a room is valid, when the sound field is diffuse. Schröder has suggested that the sound field can be regarded as diffuse if the modal overlap index is greater than 3. Based on this condition an approximation of the lowest frequency at which diffuse sound fields occur can be calculated. The so-called Schröder cut-off frequency is given by the equation (ref. [1]):

$$f_s = 2000 \sqrt{\frac{T}{V}} \text{ [Hz]} \quad (4.3)$$

where T = reverberation time of the room [s]
 V = volume of the room [m³]

The Schröder cut-off frequency as a function of the room volume has been calculated for rooms with typical living room size. The reverberation time used in the calculation is estimated from figure A1 in Annex A. From figure 4.1 it is seen that for a typical minor living room with a volume of 30 m³ a diffuse sound field - in regard of the Schröder definition - does not occur at frequencies below approximately 500 Hz.

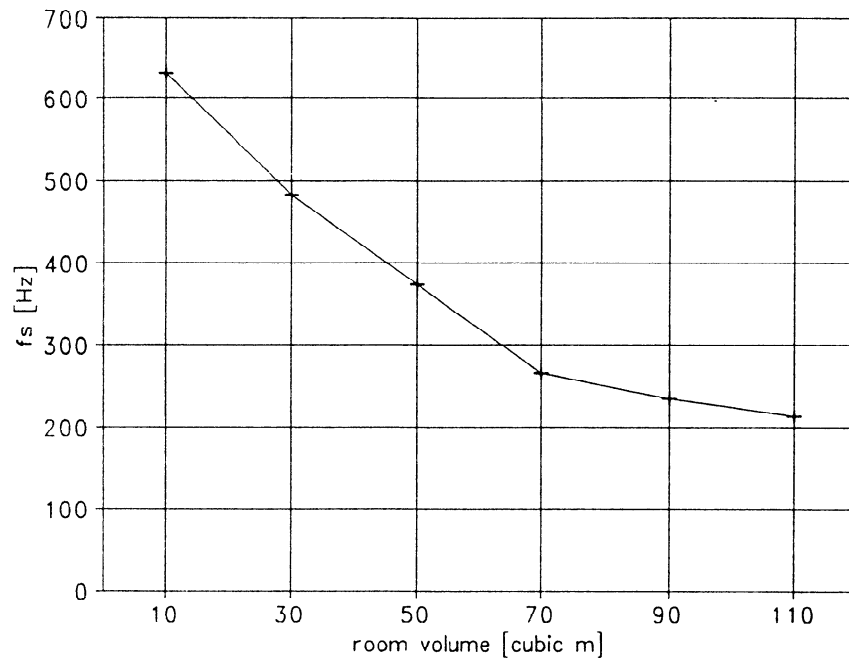


Figure 4.1. Schröder cut-off frequency as a function of the room volume.

4.2.2. Normalized standard deviation of sound pressure measurements due to spatial variations in the sound field

The sound pressure level varies with the position in a room. Lubman, (ref. [1], [3]), has derived equations approximating this position variance, even at frequencies below the Schröder cut-off frequency. It is assumed that the sound field is generated by a point source in one position.

According to Lubman the normalized spatial variance of the mean square sound pressure due to varying positions can be determined by the following equations (f_s is the Schröder cut-off frequency):

$$0.2 \cdot f_s \leq f \leq 0.5 \cdot f_s:$$

$$\varepsilon^2(p^2) = \frac{1}{1 + \frac{\eta(f) \cdot B}{\pi}} \quad (4.4)$$

where B = bandwidth of the filters [Hz]
 $(0.23 \cdot f)$

f = centre frequency of 1/3 octave band [Hz]

$\eta(f)$ = modal density for rectangular rooms

$$= \frac{4\pi \cdot V}{c^3} \cdot f^2 + \frac{\pi \cdot S}{2 \cdot c^2} \cdot f + \frac{L}{8 \cdot c}$$

where c = speed of sound in the air [m/s]
 V = room volume [m³]
 S = total area of the room surfaces [m²]
 L = $4 \cdot (l_x + l_y + l_z)$ [m]
 (l_x, l_y, l_z) length of the room edges

$f_s \leq f$:

$$\epsilon^2(p^2) = \frac{1}{1 + 0.145 \cdot B \cdot T} + \frac{1}{160^2 \cdot n} \cdot (\sqrt{A} \cdot \frac{S}{V})^3 \quad (4.5)$$

where B = bandwidth of the filters [Hz]
 $(0.23 \cdot f)$

f = centre frequency of 1/3 octave bands [Hz]

T = reverberation time [s]

V = room volume [m³]

S = total area of the room surfaces [m²]

A = absorption area of the room surfaces [m²]
 $= \frac{0.163 \cdot V}{T}$

n = shortest distance between any microphone position and the sound source in units of the reverberation distance, r_H .

$$r_H = 0.056 \cdot \sqrt{\frac{V}{T}} \text{ [m]}$$

A modification of equation 4.4 is proposed in ref. [2]. By this modification it seems that the agreement between measured and calculated results is improved. Furthermore the frequency range in which the equation is valid is extended from half the Schröder cut-off frequency to f_s . (It is stressed in [2] that the proposed modification shall be taken with reservation because of the limited documentation). The modified equation is:

$$\epsilon^2(p^2) = \frac{1}{1 + \frac{\eta(f) \cdot B}{8.5}} \quad (4.6)$$

In the following the equations 4.5 and 4.6 are used.

From the normalized standard deviation $\bar{s}(x)$ of a sample x it is possible to calculate a first order approximation of the standard deviation of x in decibels by the equation (ref. [1]):

$$s(10 \log x) \approx 4.34 \cdot \bar{s}(x) \quad (4.7)$$

For the purpose of this project the approximation in 4.7 is estimated to be sufficiently good for standard deviations $\bar{s}(x)$ less than 0.75.

As a check of the validity of the equations 4.5 and 4.6 calculation and measurement results have been compared for four different rooms having the following data:

Room no	length · width · height m	Volume m ³	Reverberation time, s		
			100 Hz	1000 Hz	3150 Hz
1	2.88 · 1.53 · 2.51	11.1	1.3	1.1	0.8
2	5.05 · 4.00 · 3.21	64.8	1.6	2.0	1.7
3	5.34 · 5.02 · 2.58	69.2	1.2	0.7	0.6
4	4.87 · 8.12 · 2.58	102.0	1.0	0.6	0.5

Table 4.1. Data of rooms used for comparison of measured and calculated spatial standard deviation of the sound pressure level.

Room 1: Toilet with hard room boundaries.

Room 2: Laboratory room with absorbers evenly distributed over the wall surfaces and the ceiling. Suspended diffusing elements.

Room 3: Furnished meeting room with carpet.

Room 4: Furnished living room with carpet.

In each of the four rooms ten sound pressure level measurements were carried out in microphone positions distributed in the total space available. (Measurement in five microphone positions for each of two loudspeaker positions. The averaging time was 30 s in each position. The reverberation time in each of the four rooms was measured in six positions on a rotating microphone boom). Ten measurements are estimated to be sufficient to give a standard deviation comparable with the theoretical calculated values.

In figures 4.2-4.5 the calculated and the measured spatial standard deviations are shown. The agreement is seen to be quite good for all of the rooms. In the smallest room with a volume of only 11 m³ great discrepancies are noticed at frequencies below 200 Hz. This is to be expected since equation 4.6 is not valid for the lowest frequencies in this room.

In the two furnished rooms with carpets the measured standard deviation exceeds the calculated values at frequencies above 2000 Hz. This is probably due to near-field influence from the loudspeaker and/or because of a non-diffuse sound field due to the highly absorbing carpets and furniture. (In the calculations the minimum distance between the loudspeaker and any microphone position is assumed to be at least 3 times the reverberation distance. This assumption is probably too optimistic).

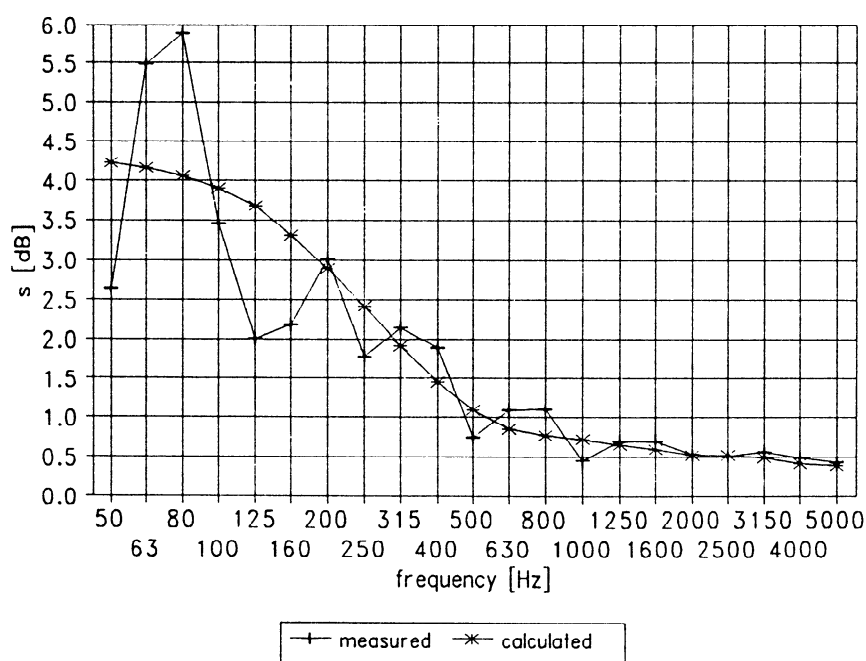


Figure 4.2. Measured and calculated spatial standard deviation of the sound pressure level in room 1.

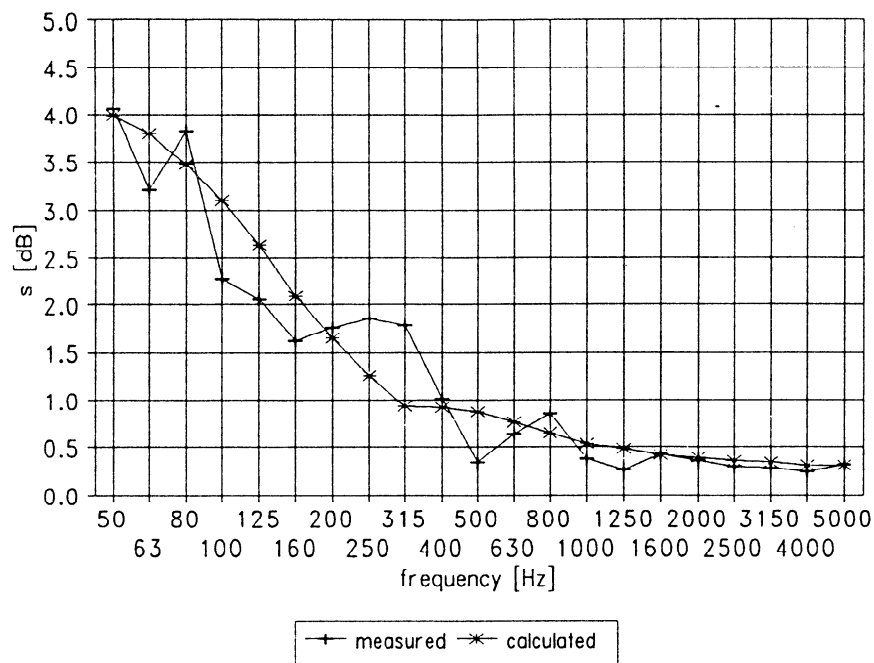


Figure 4.3. Measured and calculated spatial standard deviation of the sound pressure level in room 2.

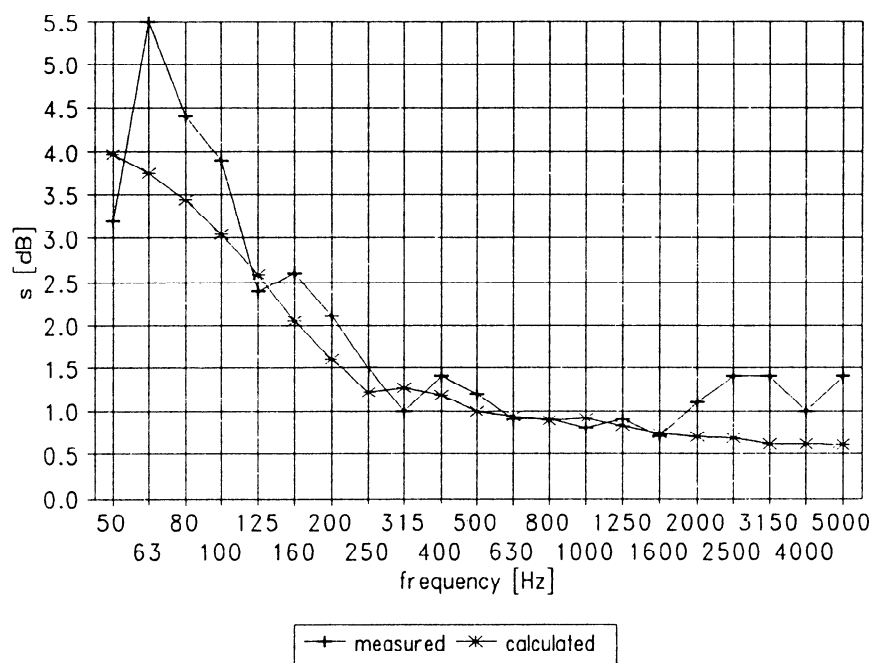


Figure 4.4. Measured and calculated spatial standard deviation of the sound pressure level in room 3.

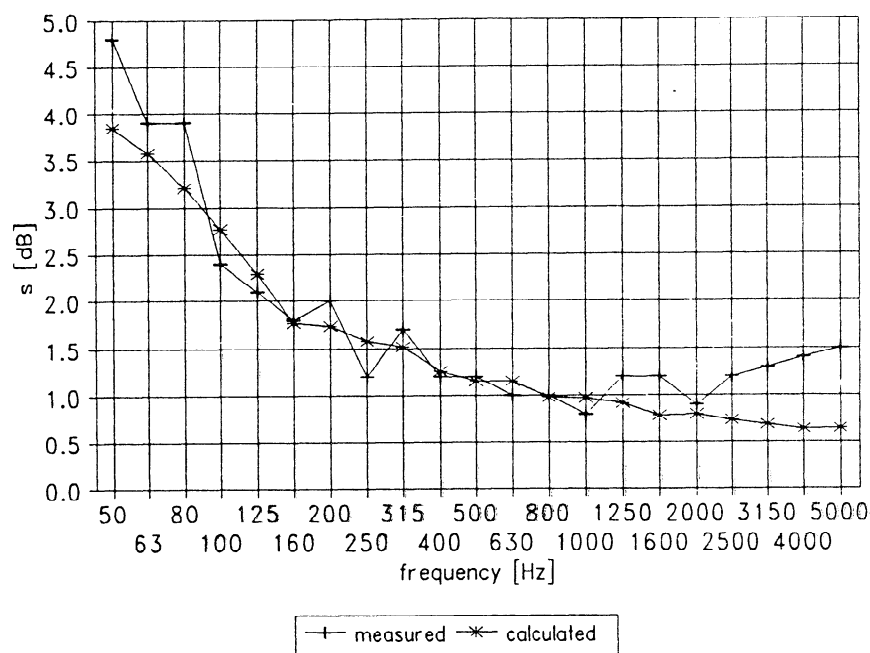


Figure 4.5 Measured and calculated spatial standard deviation of the sound pressure level in room 4.

To illustrate the spatial standard deviation for the sound pressure level in typical empty living rooms calculations have been carried out for five different rooms with volumes from 10 m^3 to 100 m^3 . The results are shown in figure 4.6. The reverberation time has been estimated from Annex A. For the 100 m^3 -room an additional calculation has been carried out assuming that the reverberation time in the entire frequency range is 0.4 s . It is seen that in this extremely damped room the standard deviation is increased considerably.

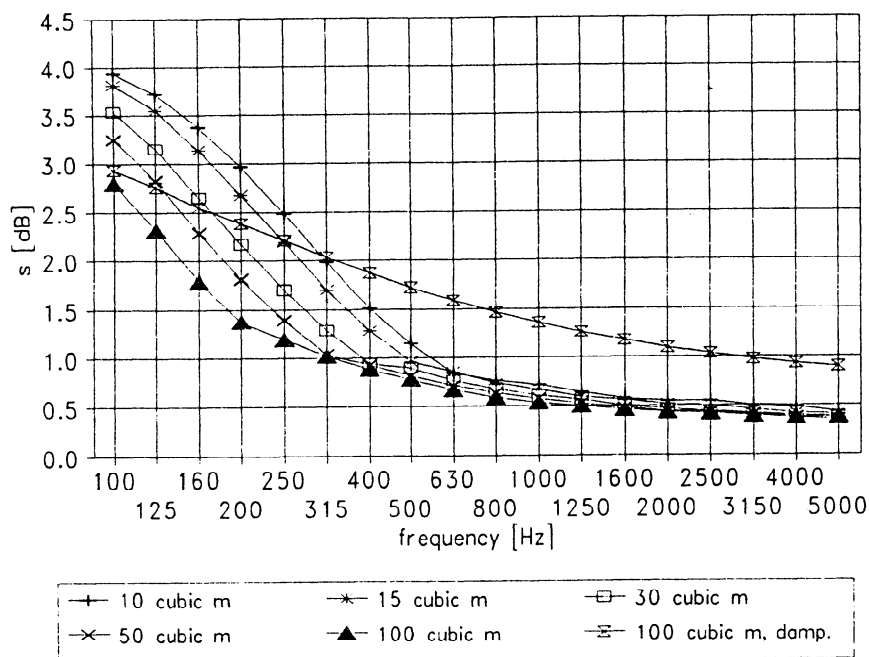


Figure 4.6. Spatial standard deviation calculated for rooms with typical living room dimensions and with volumes in the range 10 m³ to 100 m³.

4.3. LOW FREQUENCY LIMITATIONS

At frequencies below the lowest eigenfrequency of a room, wave patterns do not occur. The room is to be considered as a pressure chamber with a uniform sound pressure level distribution. The lowest eigenfrequency of a rectangular room can be calculated from the equation:

$$f = \frac{c}{2\ell} \text{ [Hz]} \quad (4.8)$$

where c = speed of sound in the air [m/s]
 ℓ = longest dimension of the room [m]

If e.g. the longest dimension of a room is 2 m wave patterns cannot occur at frequencies below 86 Hz.

At frequencies below the lowest eigenfrequency the spatial standard deviation is expected to decrease considerably.

4.4. EQUIVALENT NUMBER OF MICROPHONE POSITIONS, LOUD-SPEAKER POSITIONS AND TEST OBJECT POSITIONS

In a diffuse sound field microphone and loudspeaker positions, respectively, can be regarded as uncorrelated if the distance between them is more than half a wavelength corresponding to the lowest frequency of interest. Assuming diffuse sound fields it is possible to estimate the equivalent number of uncorrelated positions in situations where the distance between the actual positions is less than half a wavelength.

4.4.1. Rotating microphone

For a continued averaging along a circle an estimate of the equivalent number of uncorrelated fixed microphone positions can be calculated from the equation (ref. [1]):

$$N_{\text{eq,rot.mic.}} = \frac{2L}{\lambda} + \frac{1}{1 + (2L/\lambda)} \quad (4.9)$$

where λ = the wavelength [m]
 L = the length of the perimeter of the circle path [m]

In figure 4.7 the equivalent number of uncorrelated fixed microphone positions is shown for different circular microphone paths as a function of the frequency in the range 50-315 Hz.

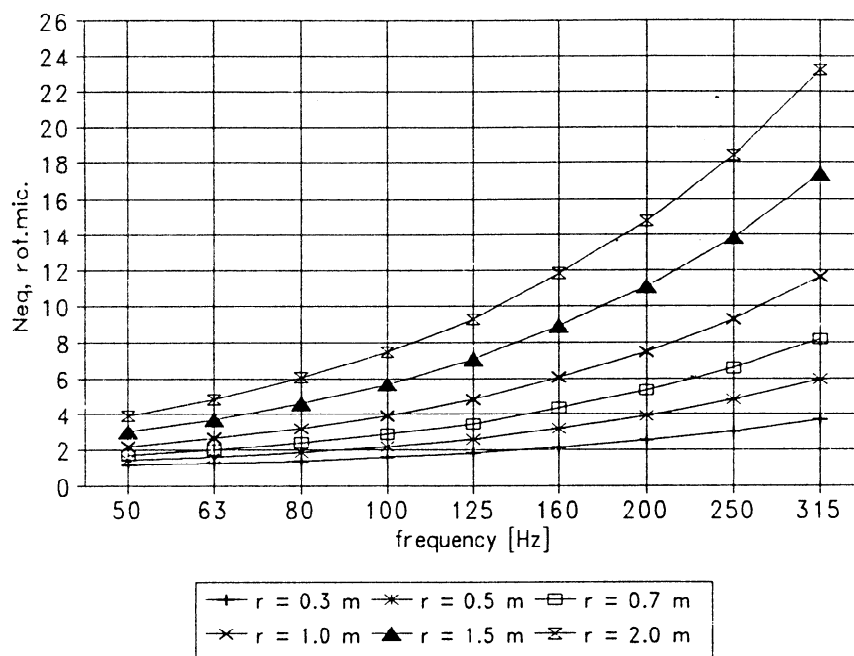


Figure 4.7. Equivalent number of uncorrelated fixed microphone positions as a function of the frequency and the radius (r) of a rotating microphone.

According to ISO 140 Part 4 the radius of a rotating microphone must not be less than 0.7 m. From figure 4.7 it is seen that in a diffuse sound field a radius of 0.7 m corresponds to three uncorrelated fixed positions at 100 Hz and less than two positions at 50 Hz.

4.4.2. Fixed microphones

For fixed microphones in a diffuse sound field with a distance between the positions less than half a wavelength the equivalent number of uncorrelated positions can be estimated from the equation (ref. [2], [3]):

$$N_{\text{eq, disc. mic.}} = \frac{N}{1 + \frac{1}{N} \sum_i \sum_j R^2(kx_{ij})} \quad (i \neq j) \quad (4.10)$$

where	N	=	the actual number of positions
	R	=	correlation coefficient for a diffuse sound field
		=	$\frac{\sin(kx)}{kx}$
	k	=	wave number [1/m]
		=	$\frac{2\pi \cdot f}{c}$
	f	=	Centre frequency of 1/3 octave band [Hz]
	c	=	speed of sound in the air [m/s]
	x_{ij}	=	actual distance between the i th and the j th discrete microphone position [m]

Calculations have been carried out for five positions with a mutual distance between all positions of 0.4 m, 0.7 m, 1.0 m and 1.5 m, respectively. Furthermore calculations have been carried out for ten positions with a mutual distance of 0.4 m. The result of the calculations in the frequency range 50-500 Hz is shown in figure 4.8.

According to ISO 140 Part 4 the minimum allowable distance between fixed microphone positions is 0.7 m and the minimum number of positions is five. From figure 4.8 it can be seen that five positions with a mutual distance of 0.7 m at 100 Hz correspond to 2.4 uncorrelated positions. (The same distance between all positions has been assumed to facilitate the calculations. Of course this cannot be achieved precisely in practice.)

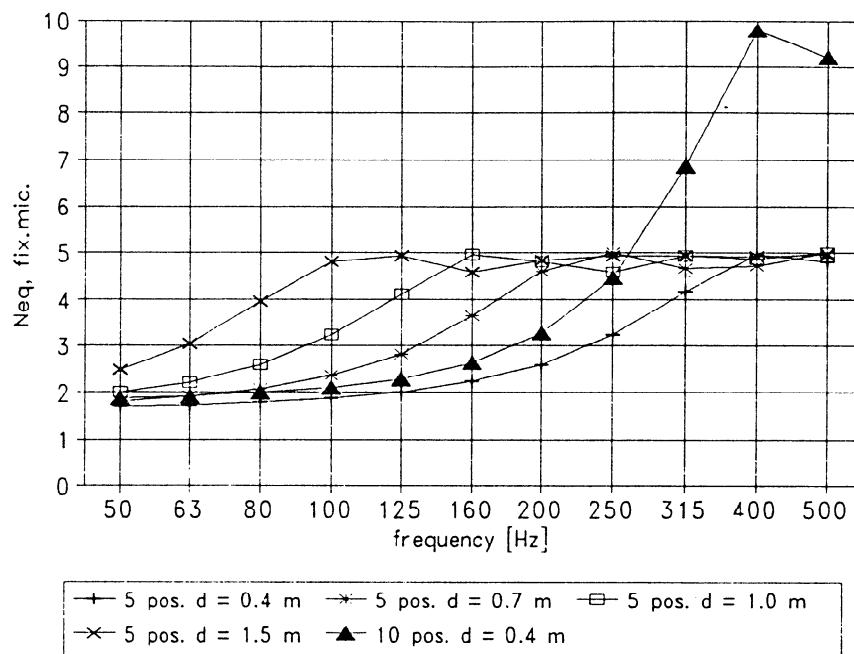


Figure 4.8. Number of uncorrelated microphone positions as a function of the frequency and the mutual distance between the actual number of fixed positions (d).

4.4.3. Test object

The test object is defined as the part of the partition wall common to source and receiving room.

The test object can be equivalated with a number of uncorrelated point sources by the following equation, ref. [1]:

$$N_{\text{eq, testobject.}} = 1 + \left(\frac{\sqrt{S}}{\lambda/2} \right)^2 \quad (4.11)$$

where S = surface area of test object [m^2]
 λ = wavelength [m]

In figure 4.9 is shown the equivalent number of point sources as a function of the frequency and the area of a test object.

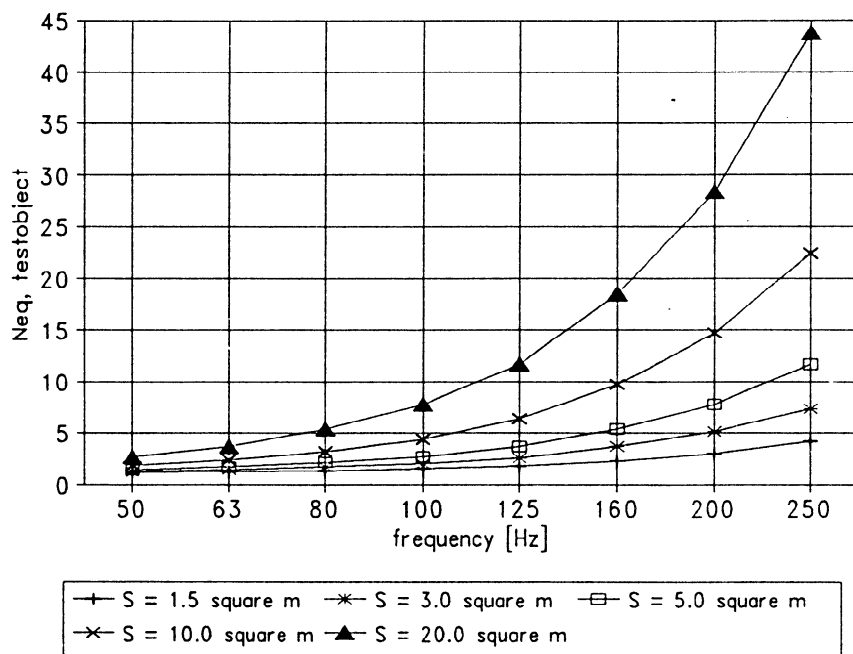


Figure 4.9 Equivalent number of uncorrelated point sources corresponding to the area (S) of a test object as a function of the frequency.

To investigate the validity of equation 4.11 an experiment was carried out in two adjacent rooms with the volumes of 69 m^3 and 102 m^3 . The common partition wall (the test object) is made of solid bricks and the area is 13 m^2 . The rooms were furnished.

In the 69 m^3 -room a loudspeaker was placed close to the wall opposite the test object and another loudspeaker was placed in the 102 m^3 -room. The sound pressure level was measured in ten microphone positions in the 102 m^3 -room with the two loudspeakers successively. When the loudspeaker in the 69 m^3 -room is used the test object is excited and acts as sound source. The standard deviation of the sound pressure level in the ten positions has been calculated for both measurements. The complete experiment was repeated for the opposite measuring direction.

The results are shown in figure 4.10. If the theory of equivalating the wall with a number of uncorrelated point sources is valid it should be expected that the standard deviation of the ten measurements should decrease when the wall is radiating the sound into the rooms compared with the results where only one source position - the loudspeaker - has been used. Apart from the lowest frequencies in the measurement from the smaller to the bigger room, this effect does not clearly appear.

At medium and high frequencies where the equivalent number of uncorrelated point sources for the wall is high a considerable decrease in the standard deviation should be expected, but does not occur.

The results of this experiment indicate that in practice equation 4.11 may overestimate the number of equivalent point sources.

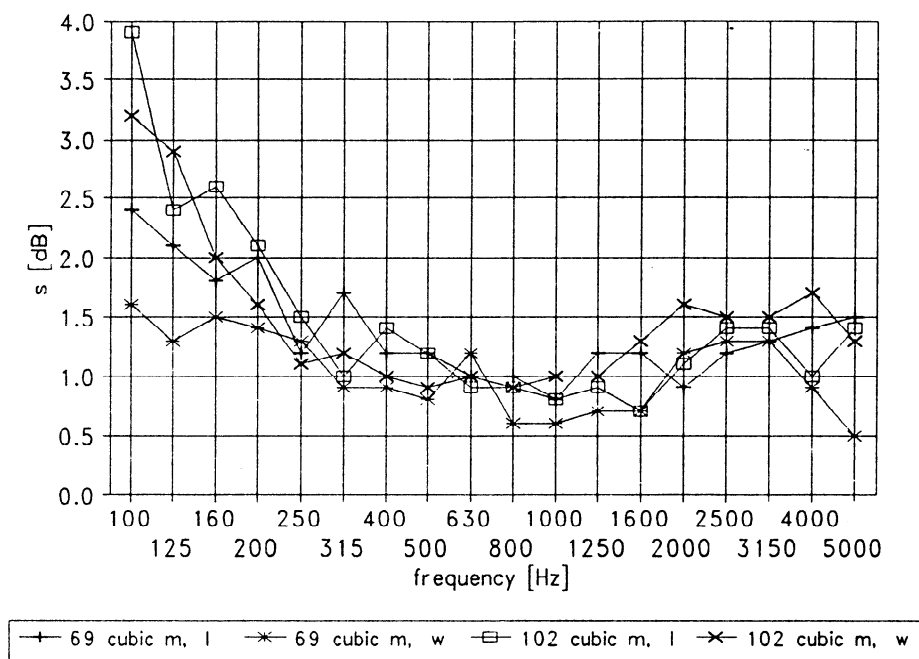


Figure 4.10. Standard deviation of the sound pressure level in ten microphone positions partly with a loudspeaker in one position as sound source (l), and partly with sound radiated from a 13 m² wall made of solid bricks (w).

4.4.4. Loudspeakers

Theoretically the loudspeaker positions can be assumed uncorrelated if the distance between them is greater than half a wavelength. At 100 Hz the minimum distance fulfilling this requirement is 1.7 m. Often two loudspeaker positions are used and - even in case of a small source room - it will normally be possible to place the loudspeaker in positions separated at least approximately 1.7 m. Therefore consideration concerning the equivalent number of uncorrelated loudspeaker positions has been omitted. It shall be mentioned that experimental results in ref. [7] show that even at a distance between loudspeaker positions of a quarter of a wavelength the positions can be considered approximately uncorrelated in a fairly reverberant room.

To investigate if the number of loudspeaker positions should be varied depending on the size of the rooms a statistical evaluation has been carried out on measurement results from routine field measurements carried out by the Danish Technological Institute (DTI).

The standard test procedure used by DTI includes two loudspeaker position and a rotating microphone in the source and receiving room, respectively. Source room level

and receiving room level are measured simultaneously. For each loudspeaker position the level difference is determined separately. The paths of the two rotating microphones are not changed during the measurement.

Results from 45 field routine measurements carried out by DTI have been analyzed by calculating the difference between the measured sound pressure level difference for each of the two loudspeaker positions. Horizontal as well as vertical measurements have been included and the volumes of the rooms are in the range of 11 m³ to 122 m³. For some of the measurements the dimensions of the source and receiving rooms are identical; for others they are very different. Normally the larger room is used as source room. For horizontal measurements the loudspeakers are placed on the floor close to the corners opposite the test object. For vertical measurements the lower room is the source room and the loudspeaker positions are as far as possible chosen to be in the corners opposite the facade.

In figure 4.11 the following results are shown:

- The mean value of the difference between the sound pressure level difference measured with the two loudspeakers in the frequency range 100-3150 Hz for the 45 measurements. ("mean value").
- Values below which 50% of the results are lying. ("50% limit").
- Values below which 90% of the results are lying. ("90% limit").
- The maximum difference observed ("max. value").

It is seen that for 90% of the measurements the difference between the results obtained with the two loudspeakers is less than 3-6 dB at frequencies below 400 Hz and less than 3 dB at frequencies above 400 Hz.

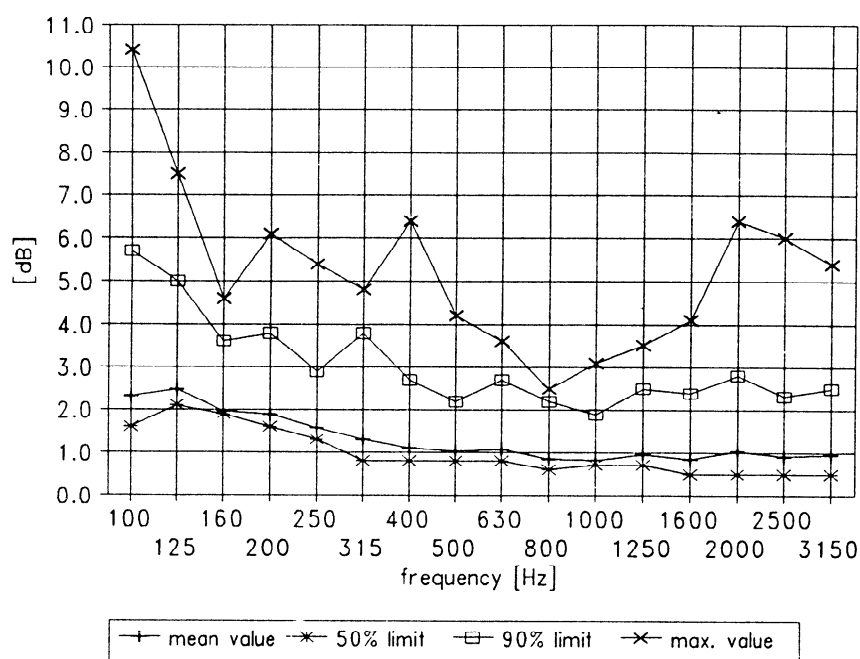


Figure 4.11. Difference between the sound pressure level difference obtained with two loudspeaker positions in 45 in-situ routine measurements.

To investigate the correlation between the volume of the source room and the difference between the sound pressure level difference measured with the two loudspeakers a linear regression analysis has been carried out. The coefficient of determination turns out to be less than 0.05 in the entire frequency range. In spite of the relatively limited statistical basis this result indicates that there is no significant correlation between the source room volume and the sound pressure level difference obtained from measurement with the two loudspeakers.

4.5. MINIMUM DISTANCE BETWEEN LOUDSPEAKER AND MICROPHONE POSITIONS

Near-field influence from the loudspeaker at any microphone position shall be avoided. The near-field influence depends on the room volume, the reverberation time and the radiation characteristic of the loudspeaker. By equation 4.12 the minimum distance from an omnidirectional loudspeaker where the influence from the near-field is negligible can be calculated. (3 times the reverberation distance):

$$d = 0.16 \sqrt{\frac{V}{T}} \text{ [m]} \quad (4.12)$$

where T = reverberation time [s]
 V = room volume [m^3]

Figure 4.12 shows calculation results of d as a function of the reverberation time and the room volume. If the loudspeaker is placed close to the room boundary - e.g. in a corner of the room - the required minimum distance estimated by equation 4.12 shall be increased by a factor 2-3. For loudspeakers which are not omnidirectional the distance must be increased further to avoid near-field influence.

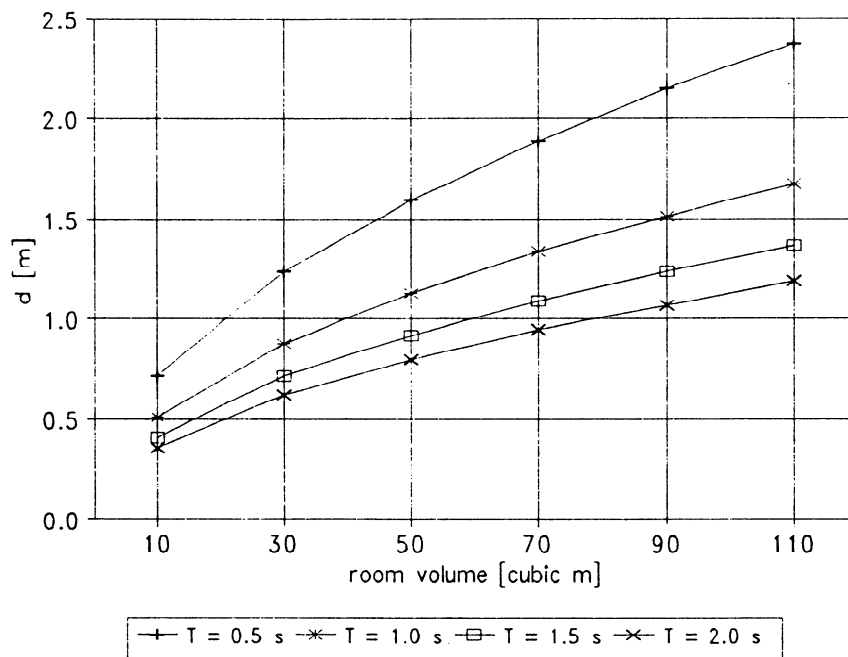


Figure 4.12. Minimum distance between an omnidirectional loudspeaker and a microphone position as a function of the reverberation time (T) and the room volume.

4.6. AVERAGING TIME

If errors due to time averaging shall be negligible compared with the position variance in the room the averaging time in each microphone position shall fulfil the following condition (ref. [2]):

$$t > 0.29 \cdot T + \frac{2}{B} \text{ [s]} \quad (4.13)$$

where T = reverberation time [s]
 B = bandwidth of the filters [Hz]
 $(0.23 \cdot f)$
 f = centrefrequency of 1/3 octave bands [Hz]

As the last term in the equation is small compared with the first one it can be derived from equation 4.13 that the averaging time in each frequency band shall be at least 3 times the reverberation time (~ 10 times $0.29 T$). ISO 140 Part 4 prescribes an averaging time in each microphone position of at least 6 s at frequencies below 400 Hz and at least 4 s at higher frequencies.

4.7. SMALL ROOMS

In small rooms - typically bath rooms and entrance halls - with volumes in the range 8-15 m³ the following problems occur causing considerable measurement inaccuracy especially at low frequencies:

- The modal overlap is small (the Schröder cut-off frequency typically 400-600 Hz).
- Room dimensions are so small that it is impossible to achieve a sufficient distance between individual microphone positions or a sufficient radius of a rotating microphone. From figure 4.7 in paragraph 4.4.1 it appears that a rotating microphone with a radius of e.g. 0.3-0.4 m corresponds to less than two uncorrelated microphone positions at 100 Hz. From figure 4.8 in paragraph 4.4.2 it appears that e.g. five fixed microphone positions with a mutual distance of 0.4 m also correspond to less than two uncorrelated positions at 100 Hz.
- It is difficult to achieve a sufficient distance between loudspeaker and microphone positions so near field influence is avoided. From figure 4.12 it can be seen that in a 10 m³ room with a reverberation time of 0.5 s the minimum distance between loudspeakers and microphones shall be approximately 0.75 m to avoid near field influence. In small rooms it is necessary to place the loudspeakers close to the corners. This means that the minimum distance estimated according to figure 4.12 should at least be doubled.

- Often it is impossible to achieve sufficient distance between the loudspeaker positions.

It can be estimated that if the measurement accuracy of the mean sound pressure level in e.g. a 10 m³-room and a 100 m³- room shall be of the same magnitude at low frequencies, the number of uncorrelated microphone positions in the 10 m³-room shall be increased with approximately a factor 10 compared with the number used in the 100 m³-room.

The increase in the position variance of the sound pressure level in small rooms with volumes of 8-15 m³ might imply that the number of loudspeaker and/or microphone positions should be increased to achieve a measurement accuracy of the mean value comparable to that obtained in bigger rooms. However, the small room volume makes it impossible to fulfil the requirements to minimum distances stated in ISO 140 Part 4. Furthermore, the number of positions required, if the measurement accuracy shall be improved considerably will be so high that the guidelines will be inapplicable for routine measurements. Therefore it is suggested that it generally is accepted that the measurement accuracy is decreased in small rooms in which the ISO 140-procedure cannot be fulfilled.

Especially the use of a rotating microphone is problematic if the minimum radius and the minimum distance to the room boundaries shall be fulfilled.

4.8. DAMPED ROOMS

In typical living rooms with volumes of 50-100 m³ the sound field normally can be regarded as approximately diffuse provided that the room surfaces are made of normal building materials such as plasterboard, bricks, concrete and wood. Even if the floor is covered with a carpet, the measurement conditions still normally will be sufficiently good. This means that averaging the sound field by measuring in several microphone positions distributed in the room will give a fairly good mean value of the sound pressure level for the determination of the sound reduction index.

The equation used for calculating the sound reduction index assumes that the incident sound power on the test object and the total sound power radiated into the receiving room are determined from averaging the sound pressure levels in a diffuse field in source room and receiving room, respectively. Under ideal conditions the purpose of the averaging is just to reduce the influence on the measurement result of unavoidable random variations in the sound field.

However, in rooms with high absorption as e.g. furnished living rooms, offices, classrooms, auditoria, corridors and industrial halls the sound pressure level often decreases considerably with increasing distance to the sound source. This phenomenon causes measurement problems, especially in big rooms or rooms where the width of the room is small compared to the length. In such rooms a correct estimate of the incident and radiated sound power is not possible.

In the free-field region close to a sound source the sound pressure level will decrease by 6 dB per doubling of the distance to the sound source. In the diffuse-field region no systematic decrease in the sound pressure level far away from the loudspeaker will occur if the distance to the sound source is increased. In strongly damped rooms the decay rate of the sound pressure level far away from the loudspeaker can typically be 3-4 dB per doubling of the distance from the source.

To get an impression of the magnitude of the sound decay rate in damped and non-damped rooms with different shapes, a few calculations of the sound pressure level distribution have been carried out by use of the computer programme "Odeon" developed by the Acoustical Laboratory at the Technical University in Denmark. The size of the rooms in the calculations have been chosen corresponding to "big living rooms". The calculation results are presented in Annex B. From the calculation examples it is seen that with high absorption of ceiling and floor a considerable decay of the sound pressure level occurs.

In ISO 140 Part 4 it is stated that the microphone positions shall be distributed within the maximum permitted space throughout the room, taken in the room space uniformly. ISO 140 Part 4 assumes diffuse sound fields and nothing is stated explicit concerning loudspeaker and microphone positions in damped rooms.

If a logarithmic averaging of the sound pressure level in positions spread over the entire volume is used in a big damped receiving room, the positions in the part of the room closest to the test object will dominate the average value. This average value, however, equals to some extent the average sound pressure level in "the same room" determined under diffuse field conditions. Consequently, averaging over the entire volume in damped receiving rooms leads to a fairly good approximation of the sound power radiated into the room.

In the source room the problems are different. From the average sound pressure level the incident sound power on the test object is determined. In big, damped rooms averaging over the entire room volume often will lead to considerable errors. This can be illustrated by an example:

The sound insulation is measured horizontal between two rooms. The source room is big, with a highly absorbing ceiling and floor and the width of the room is assumed much less than the length (e.g. the corridor in example 1, Annex B.3). Loudspeaker positions are chosen close to the corners at the back wall of the room opposite the test object, which is assumed to be the wall designated "2,50 m" in Annex B.3. The sound pressure level is measured in positions distributed evenly in the total room volume, which means that the sound pressure level measured at the positions close to the loudspeaker will be dominating the average sound pressure level. In example 1, Annex B.3, the mean sound pressure level averaged over the entire room volume is estimated to be 7 dB higher than the sound pressure level in the part of the room close to the test object. It appears from this example that averaging over the total volume in big, damped source rooms leads to a bad estimate of the incident sound power on the test object.

If the flanking transmission between the rooms in the example is considerable, another problem arises. Because of the loudspeaker positions far away from the test object and at the same time close to the flanking walls, the excitation of these will be high compared with the excitation of the test object. In the extreme situation, exclusively the flanking transmission will be determined based on near-field influence from the loudspeaker and the contribution of the sound transmitted directly through the test object will have an unrealistically low influence on the measurement result.

In the extreme situation where the source room can be approximated with free-field conditions, the measured sound reduction index will be different for each angle of incidence of sound upon the test object. Especially at frequencies in the coincidence region the results are expected to be too high compared with results from diffuse-field measurements. (Incident sound parallel to the test object is reduced under free-field conditions.)

As a consequence of the consideration above it might be a possibility to improve the measurement conditions in big source rooms by moving the loudspeaker positions towards the test object. Averaging in a limited part of the room not too far away from the test object will reduce the error because of the spatial sound decay in the room, and furthermore ensure an equal weighting of the incident sound power on the test object and the flanking walls, respectively.

In very damped rooms which imply free-field conditions, measurements should not be carried out according to the ISO 140 procedures. The intensity measurement technique is a suitable alternative for the determination of the sound power radiated into the receiving room. (Nordtest Method NT ACOU 084 can be used.)

For vertical measurements between damped rooms, the problems are not so serious because the sound pressure level decay in vertical direction is limited to a distance equal to the height of the rooms.

4.9. BIG ROOMS AND ROOMS WITH NON-REGULAR SHAPE

When measuring the sound insulation between regular box-shaped rooms with typical living room size, not too different in size and not too "staggered", the selection of loudspeaker and microphone numbers and positions does not normally cause particular problems. However, in case of big rooms, staggered rooms or rooms with non-regular shapes, it often can be rather difficult to choose a suitable measurement set-up. Non-regular room shapes are frequently seen in modern dwellings.

The question can typically be if the minimum number of loudspeaker and microphone positions stated in ISO 140 Part 4 shall be increased in big rooms, and where to place the loudspeaker and the microphones in a room with non-regular shape e.g. an angular shaped room, a room partly divided by a wall or a very long, narrow room. A detailed theoretical or experimental investigation of the measurement accuracy in such rooms is extremely complicated and in excess of the scope of this project. Principles for the choice of suitable measurement set-ups in non-regular rooms have therefore been

worked out partly based on the consideration and results in the previous chapters and partly on practical experience.

Some typical non-regular shaped room configurations are shown in Annex C. The loudspeaker and microphone positions indicated in Annex C are described in chapter 4.14.

4.10. DETERMINATION OF ROOM VOLUME AND AREA OF THE TEST OBJECT

In regular box-shaped rooms without any fixtures the determination of the volume of the receiving room and the area of the test object is self-evident. However, in rooms such as kitchens, sculleries and bathrooms with fixtures like cabinets, wardrobes and installation shafts the calculation of volume and area require some attention.

The problem is to decide whether fixtures can be neglected or not. Figure 4.13 shows calculation results of the error introduced on the sound reduction index measurement, as a function of the ratio in percentages between two room volumes or two test object areas. If e.g. the volume used in the calculation is 10% too big because the volume of the fixtures has not been subtracted, the measurement result will be 0.5 dB too low. If a reduced test object area is used in the calculation e.g. because fixed cabinets are covering a part of the wall, the measurement result will be lower than the result obtained if the entire wall area is used.

In a minor kitchen with a volume of 35 m³ the cabinets etc. will often reduce the total room volume with 5-6 m³. If the total volume is used in the calculation the error will be approximately 1 dB.

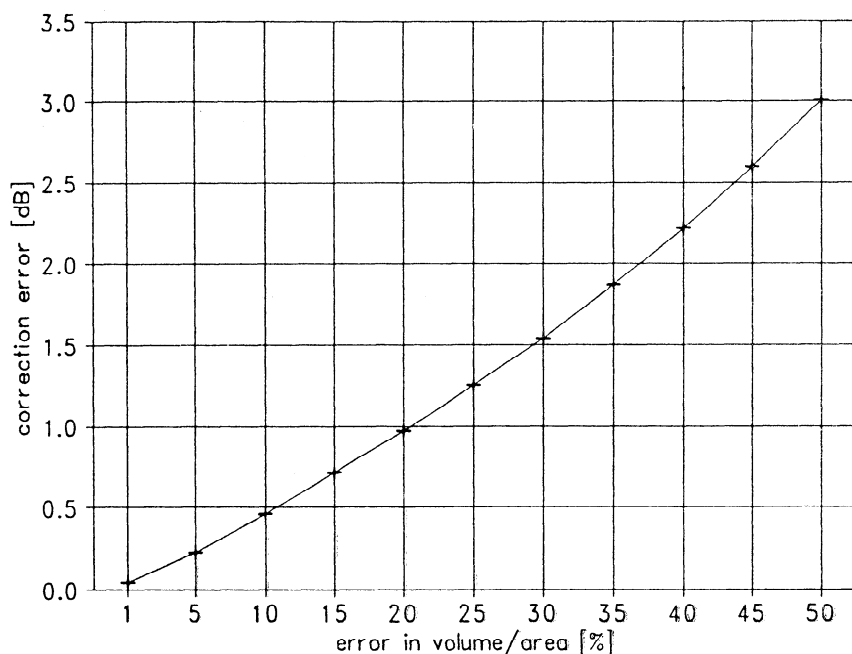


Figure 4.13. Measurement error as a function of error in room volume or test object area expressed in percentages.

For a room to some extent separated by a wall it often can be difficult to decide if the room shall be regarded as one or two volumes. This type of rooms typically will be a combined living room and kitchen where the kitchen section is partly separated from the living room by a wall.

In special cases it can be almost impossible to define the room volumes to be used for the measurements. This is e.g. the situation where two or three rooms with complicated ground planes are situated on displaced storeys and more or less coupled together by openings for stairs etc.

4.11. REVERBERATION TIME

For the determination of the sound reduction index the reverberation time in the receiving room shall be determined.

In ISO 140 Part 4 the requirements concerning measurement of the reverberation time are based on ISO 354, in which it is prescribed that as a minimum three microphone positions shall be used. At frequencies below 300 Hz at least two loudspeaker positions are required. The minimum number of measurements required for each frequency band is twelve decays at frequencies from 100-250 Hz, nine decays from 315-800 Hz and six decays from 1000-5000 Hz.

In ISO 140 Part 4 the requirements in ISO 354 have been somewhat modified and it is required that at least one loudspeaker position and three microphone positions with two excitations in each position shall be used. The six readings can alternatively be taken on a rotating microphone path with a traverse time not less than 30 s.

To assess the accuracy of the reverberation time measurement according to ISO 140 Part 4 a comparison between the spatial standard deviation of the sound pressure level and the reverberation time has been estimated from measurements in room 2, described in table 4.1, chapter 4.2.2. The sound pressure level as well as the reverberation time were measured in the same ten microphone positions (five for each of the two loudspeaker positions). In each microphone position two reverberation decays were taken. The standard deviation of the reverberation time measurement has been approximated in decibels ($10\log(T)$) by means of equation 4.7.

Figure 4.14 shows the measurement result. It appears that at frequencies below 500 Hz the standard deviation of the reverberation time measurement is much less than the standard deviation of the sound pressure level measurement. At 500 Hz and higher frequencies the difference between the standard deviations is decreased considerably, but still inaccuracy due to the sound pressure level measurement is predominant. From figure 4.14 the standard deviations of the sound pressure level difference and the reverberation time, respectively, have been estimated based on the number of microphone positions used in a realistic measurement situation. This does not cause essential change in the ratio between the two standard deviations.

Thus the results in figure 4.14 indicate that the modification of ISO 354 requirements used in ISO 140 Part 4 is reasonable, and the inaccuracy due to the reverberation time measurement is normally small compared with the inaccuracy of the sound pressure level measurements.

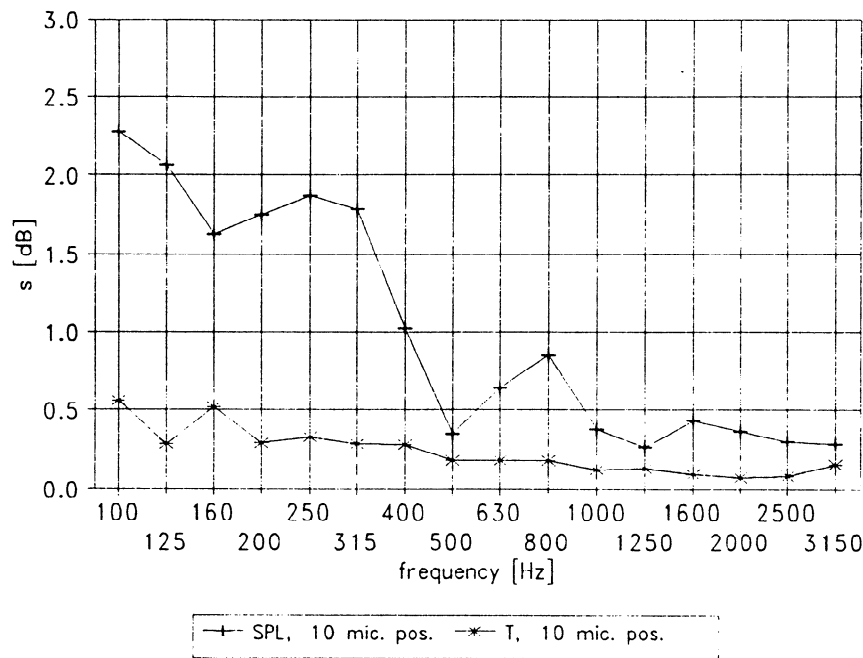


Figure 4.14 Spatial standard deviation of the sound pressure level and the reverberation time measured in ten positions in a 65 m³ room. Two excitations in each position for the reverberation time measurement.

4.12. SUMMARY OF REQUIREMENTS IN ISO 140 PART 4 CONCERNING LOUDSPEAKER- AND MICROPHONE POSITIONS

Summary of the requirements in ISO 140 Part 4 concerning number and position of sound source and microphones:

- One loudspeaker may be moved from position to position or several loudspeakers may be operating simultaneously provided that they are driven by uncorrelated noise generators and different power amplifiers.
- At least two loudspeaker positions shall be used.
- The distance between different loudspeaker positions shall be not less than 0.7 m. At least two positions must be situated not less than 1.4 m from each other.
- The distance between room boundaries and the loudspeaker shall be not less than 0.5 m. Small irregularities of the room boundaries may be neglected.
- Different loudspeaker positions may not be situated within the same planes parallel to the room boundaries.

- Especially in small rooms often it is an advantage for the practical execution of the measurement to use loudspeaker positions in the corners of the source room. Special care must be taken in regard to possible influence on the flanking transmission and in regard to unwanted increase of level fluctuations in the source room.
- If the rooms are of different volumes the larger one should be chosen as source room when the standardized level difference is to be evaluated and no contradictory procedure is agreed upon.
- In order to evaluate the apparent sound reduction index the loudspeaker positions may be in the same room or the measurement may be repeated in the opposite direction by changing source and receiving rooms with one or more positions in each room.
- The loudspeaker should be placed so as to give a sound field as diffuse as possible and at such a distance from the partition element and the flanking elements influencing the sound transmission, that the direct radiation on these is not dominant.
- The average sound pressure level can be obtained by using a single microphone moved from position to position, by an array of fixed microphones, by a continuously moving microphone or by swinging a microphone. The sound pressure level at the different microphone positions shall be averaged on an energy basis for all sound source positions.
- As a minimum five microphone positions shall be used being distributed within the maximum permitted space throughout each room taken in the room space uniformly.
- When using a moving microphone the sweep radius shall be not less than 0.7 m. The plane of the traverse shall be inclined in order to cover a large proportion of the permitted room space and shall not lie in any plane within 10° of a room surface. The duration of a traverse period shall be not less than 15 s.
- The following separation distances are minimum values and should be exceeded where possible:
 - 0.7 m between microphone positions.
 - 0.5 m between any microphone position and room boundaries or diffusers.
 - 1.0 m between any microphone position and the sound source.
- It must be ensured that the microphone positions are outside the direct sound field of the source. Each fixed microphone position shall lie outside the region in which levels increase significantly with distance from the source. For a moving microphone, no significant level increase shall occur when the path comes close to the source.