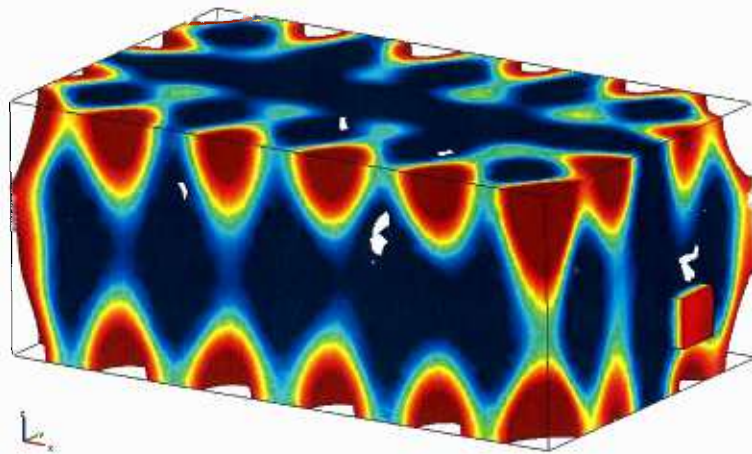




Finnish Institute of
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Measurement of low frequency noise in rooms

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TIIVISTELMÄ

Äänenpainetasot riippuvat matalilla äänentaajuuksilla (20-200 Hz) voimakkaasti mittauspisteestä normaalikokoisissa huoneissa. Äänenpainetasojen vaihtelut ovat jopa yli 20 dB huoneen eri osissa. Tällaisen melun mittaamiseksi ei ole kuitenkaan olemassa standardisoitua menetelmää. Tutkimus aloitettiin vertailemalla kirjallisuudessa julkaistuja mittaamenetelmiä. Yksinkertaisin menetelmä määrittää vain yhden mittauspisteen ja yhden tunnin pituisen mittauksen. Tämä lähestymistapa ei huomioi huonemoodeja lainkaan ja tuloksista voidaan vetää vääriä johtopäätöksiä. Kehittyneemmät menetelmät korostavat mittaamista nurkissa, jotka johtavat äänenpainetason yliarviointiin käyttäjään kokemukseen nähden. Myös tieteellisestä kirjallisuudesta puuttuu yksinkertainen, käyttäjän kokemusta kuvaava mittaamenetelmä.

Tutkimuksen tavoitteena oli kehittää yksinkertainen ja luotettava mittaamenetelmä pientaajuuiselle melulle, joka sopisi kaikenlaisiin huoneisiin kuten asuntoihin, potilashuoneisiin tai teollisuusvalvomoihin. Menetelmän pohjaksi tehtiin laajoja äänenpainetason mittauksia viidessä huoneessa. FEM-mallinnusta käytettiin lisäksi täydentämään analyysiä äänenpainetasojen paikkariippuvuudesta. Ehdotettava menetelmä sisältää kaksi vaihtoehtoa, ajallisesti vakion ja ajallisesti vaihtelevan melun mittaamenetelmän. Ensimmäinen on hyvin nopea ja sitä sovelletaan aina ensimmäisenä. Jälkimmäiseen sisältyy pitkän aikavälin mittaus, jota sovelletaan tarvittaessa. Useimmissa tapauksissa nopeampi menetelmä on riittävä todentamaan, täytyvätkö melutason raja-arvot. Mittauspisteiden valinnassa päähuomio on kiinnitetty tilan käyttäjään. Menetelmän soveltamista käytäntöön demonstroidaan yhdessä huoneessa. Tulevaisuudessa menetelmää tulisi markkinoida standardisointia kehittäviin komiteoihin.

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ABSTRACT

Sound pressure levels (SPL) at low frequencies (20 to 200 Hz) are strongly dependent on measurement position in normal-sized rooms. The variation of SPL can be above 20 dB between different measurement locations. However, there is no standardized method to measure such noise. Firstly, published measurement methods of low frequency noise were compared. The simplest methods specify only one measurement point and a 1-h long measurement. This approach does not consider room modes and it can result in false conclusions. More advanced methods emphasize the corner positions, which lead to the overestimation of SPL in respect with occupant's locations. The literature lacks a simple but occupant-oriented measurement method.

The aim of the study was to develop a simple and reliable method for the measurement of low frequency noise in all kinds of rooms, like dwellings, industrial control rooms or patient rooms. The method was developed on the basis of extensive measurements in 5 rooms. In addition, finite element modelling FEM was used to supplement the analysis of spatial SPL variations. The suggested method includes two alternatives for constant and for intermittent noise. The former is very rapid and it is applied in the first place. The latter includes also a long-term measurement which is applied when temporal variations are observed or expected. In most cases, the constant noise method is sufficient to state whether the limit values are exceeded or fulfilled. The main attention is paid to the occupants' locations. The practical application of the method is demonstrated in one case room. The method should be proposed to technical committees making new standard proposals.

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1 INTRODUCTION AND OBJECTIVES

In 2006, the Finnish Institute of Occupational Health (FIOH), performed a literature review [1] about low frequency noise. It aimed to clarify several questions dealing with the physical behaviour of low frequency noise (LFN) and auditory effects of low frequency noise.

The sound fields in rooms at low frequencies are complicated because of individual room modes. The variation of SPL at low frequencies inside an enclosure can be above 20 dB. The SPL measurements become very uncertain because measurement in one position, or even a few positions, cannot be used to describe the experienced sound field in general.

Some measurement methods have been specially designed to reduce the uncertainty and to improve the reproducibility at low frequencies, but still it is not clear worldwide which method are the most appropriate for practical use. Some methods focus on the experienced sound field. That is, they suggest measurements only on occupant's positions in the room. The repeatability can be low because different measurement technicians may have different criteria to choose the measurement locations. Other methods perform the measurements close to the corners where the maximum SPL is normally found. The repeatability of those methods is better but it is not clear how the measured values should be compared against the target values.

Target values for noise levels are not harmonized between countries. Harmonization would be useless as long as different measurement methods are applied.

The aim of the study was to develop a simple and reliable method for the measurement of low frequency noise in all kinds of rooms, like dwellings, industrial control rooms or patient rooms. The method focuses on the perceived noise level in the room. The method is presented in Chapter 6. Chapters 2-4 contain the descriptions of the field measurements and modelling work which was used as an experimental background for suggesting the measurement method.

This study does not suggest any target values of low frequency noise but it focuses on the measurement method itself.

2 THE STATE OF THE ART

2.1 Human perception of low frequency noise

The hearing range as a function of frequency and sound pressure level is shown in Figure 1. The standardized hearing threshold and equal-loudness contours are shown in Figure 1 [2]. We are most sensitive to frequencies between 1000 and 5000 Hz. Below 1000 Hz, the sensitivity of hearing reduces strongly. In addition, the response to level is not linear through the audible frequency range. The subjective sensation of loudness is more sensitive at low frequencies than at high frequencies. E.g., an increment of 5 dB at 20 Hz is equivalent to an increment of 10 dB at 1 kHz, when we look at the change in subjective sensation of loudness. Therefore, once low frequencies are heard they become fast uncomfortably loud. The differences in threshold and loudness perceptions between individuals are larger at low frequencies than at high ones [3]. This may explain why some individuals are more sensitive to LFN than the others. However, there is no scientific evidence that the complainants of LFN were, in general, more sensitive to low frequency sounds than the average population.

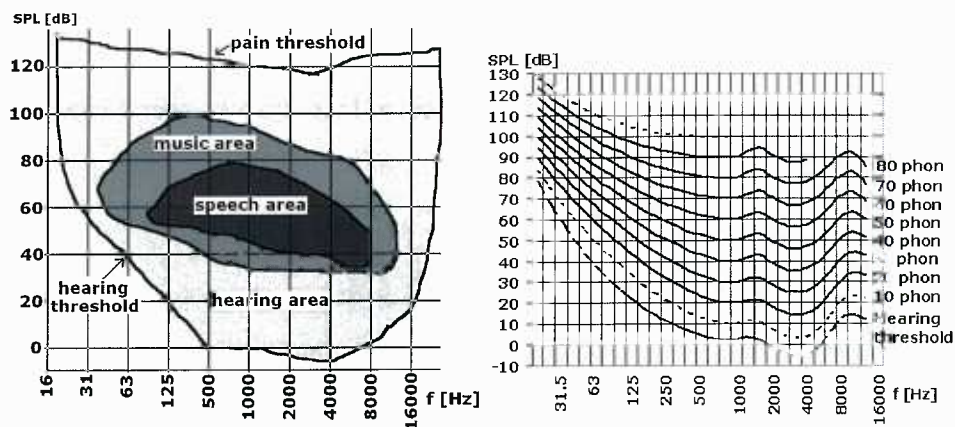


Figure 1 Left) Approximate hearing range as function of frequency and sound pressure level. Right) Hearing threshold and equal loudness contours. ISO 226:2003 [2].

In order to assess sound pressure levels and loudness objectively and rapidly, different filters are used to weight sound pressure levels as a function of the frequency. Those filters have been developed to approximate the characteristics of the human auditory system. The frequency weighting filters are not based on the curve of hearing threshold, but on the equal-loudness contours, Figure 1. The currently used A, B, and C- filters aim to mimic ISO- equal loudness curves of low, medium, and high loudness levels, respectively.

The perception of noise is strongly affected by the location where it is suffered, our control over it, and its sound pressure level over other noise sources. It is not the same to listen to the noise at day-time when we work than at night-time when we try to fall into sleep. Our reaction to the noise is also affected by its characteristics, i.e. its tonality and impulsiveness. Annoyance and human perception to noise are not dealt

with in this report. More information about LFN's annoyance and its effect on people has been published elsewhere [4,5].

2.2 Room modes

Room modes, sometimes called standing waves, result from a coincidence where the sound wave, examined in a certain point, returns to the same point after two or more reflections from the room boundaries and interferes with the original sound wave in the same phase. The sound travels the same path ideally infinite times. As a result of this, the sound pressure level depends strongly on location. Room modes appear at certain frequencies, called room resonance frequencies or eigenfrequencies where the length of the path described above is a multiple of wavelength.

At room modes there will be fixed points in the room where the waves will amplify each other to produce antinodes (sound pressure is high) and other points where complete or partial cancellation occurs to produce a node (sound pressure is zero). These points determine the highest and lowest sound pressures in the room. In spaces with parallel walls, no furniture or fittings, and low sound absorption, repeated reinforcement and cancellation may lead to very strong nodes and antinodes.

The resonance frequencies of a box-shaped room can be calculated according to

$$f_{lmn} = \frac{c_0}{2} \left[\left(\frac{l}{L_x} \right)^2 + \left(\frac{m}{L_y} \right)^2 + \left(\frac{n}{L_z} \right)^2 \right]^{1/2} \quad l, m, n \geq 0 \quad (1)$$

where L_x , L_y and L_z are the three dimensions of the room [m] and $c_0=344$ [m/s] is the speed of sound on the air in normal conditions of temperature and air pressure.

Modes occurring along one dimension of the room are called axial modes. If the room walls are parallel and $L_x > L_y > L_z$, the first axial mode $lmn=100$ occurs along the length of the room. Its node would be in the middle of the room and the antinodes by the walls. According to Eq. (1) the first resonance mode occurs at the frequency whose wavelength is half the length of the room. The second axial mode would be $lmn=200$ if $L_x > 2L_y$, otherwise $lmn=010$. Modes happening along two dimensions of the room are called tangential modes, i.e. $lmn=110$ or $lmn=201$. Finally, oblique modes occur along the three dimensions, i.e. $lmn=111$ which runs along the grand diagonals from opposite corners. A representation of the axial, tangential and oblique modes is shown in Figure 2.

Room modes are mostly responsible of spatial SPL variations within rooms. Spatial variations are the largest at low frequencies where the lowest room modes occur. When the sound field is studied one frequency at a time, the strongest SPL differences between different points are expected at the resonance frequencies. When the measurements are performed in frequency bands, e.g. 1/3-octave bands, the variation of SPLs becomes smaller because several room

modes belong to the same frequency band and they interfere with each other producing a more diffuse field. Ideally, the diffuse sound field presupposes that the sound enters to any point of the room evenly from all directions, that is, the sound intensity vector is zero. The density of room modes increases with the frequency. Therefore, the higher the frequency is, the smaller is the spatial variation of SPL, and the more diffuse becomes the sound field. The *spatial variation* of SPL means the difference between the maximum and minimum SPL.

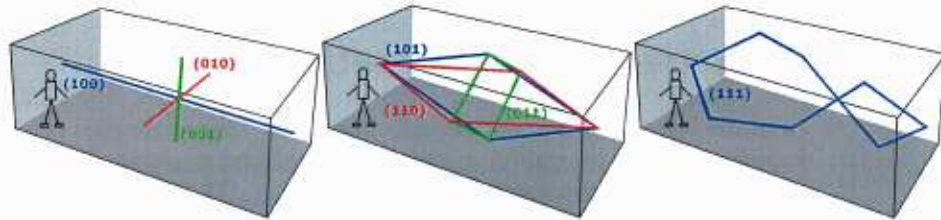


Figure 2 Left) Axial modes (100), (010) and (001). Center) Tangential modes (110), (011) and (101). Right) Oblique mode (111).

Eq. (1) does not give information about the spatial variation of SPL at the resonance frequencies or the location of the maximum and minimum SPLs. Sophisticated modelling methods which solve the wave equation of sound at every point in the space can be applied. One aim of this study was to find out about what are the real possibilities of Finite Element modelling method to solve the SPL in the room. Measurements covering the whole room space could be also performed. Both methods are needed to completely understand the behaviour of sound in rooms. Although modelling is an easier way to produce data about the spatial distribution of SPL, it contains more uncertainties than measurements. However, measurements are more laborious to carry out.

2.3 Technical considerations of low frequency noise

Environmental noise is typically wide band noise. In most cases, appropriate results in environmental noise control are reached when technical calculations are made in the frequency range 50-5000 Hz and results are given in A-weighted SPLs. In certain cases, like engine or HVAC (heating, ventilation and air conditioning) noise, some frequencies are more represented than the others and noise can have a tonal character. Special problems can appear in situations where external noise is dominated by low frequencies (20-200 Hz) presented at high sound pressure levels.

There are several technical reasons why LFN should be treated differently from noise in general, although LFN is actually nothing else than just noise. When we look the sound propagation outdoors, the atmospheric absorption is low at low frequencies. The absorption of ground and other natural boundaries are negligible at low frequencies. Therefore, the spectral content of any noise is biased towards low frequencies when it has travelled long distances. The influence of noise barriers and obstacles is also weak against LFN because of diffraction effects: sound bends over obstacles more easily at low frequencies. In building facade structures, low frequencies are significantly more intrusive than high frequencies. The sound insulation of facade

components is typically less than 15 dB below 50 Hz when it is more than 40 dB above 1000 Hz. In addition, some parts of the building can vibrate in resonance with low frequencies. For example, typical intermediate floors resonate at infrasound frequencies between 8 and 20 Hz. Finally, when sound enters the room, the room modes are strongest at low frequencies. Absorption of room boundaries is negligible at low frequencies. As a result of this chain, where all factors favour the amplification of LFN, even small levels of LFN outside the room may become extremely annoying inside the room.

2.4 Existing measurement methods

Uneven distribution of sound leads to uncertainties in noise level measurements in rooms especially at low frequencies. All standardized room acoustic measurement methods, e.g., ISO 10052, ISO 140 series, ISO 354, and ISO 374x series, presume that the acoustic field of the room is diffuse. Ideally, the diffuse sound field presupposes that the sound enters to any point of the room evenly from all directions, that is, the sound intensity vector is zero. In addition, the spatial uniformity of SPL is perfect within the room. These presuppositions always fail more or less in real rooms. Measurements in real sound fields are made, e.g., in few random points located farther than 75 cm from room boundaries (quarter wavelength of 111 Hz) and the average SPL is determined. This measurement method enables the determination of the average SPL in typical living rooms quite well above 100 to 300 Hz, depending on the room volume, but fails perfectly at lower frequencies. When the wavelength of sound is comparable to the room dimensions, the spatial variations of SPL can be above 20 dB.

The *uncertainty of measurement* describes the reliability of a certain measurement result in respect with infinite measurements made to describe the same phenomenon. The uncertainty of measurement methods is typically determined by two quantities: reproducibility and repeatability. The *reproducibility* is the difference between successive measurements carried out by different measurement operators. It is related to the randomness in the selection of the measurement locations. Therefore, the reproducibility of any measurement method which allows the measurement locations to be arbitrarily selected will be low, unless the sound field is diffuse. The uncertainty will be in the same order of the spatial variation of SPL in the room, when the measurement locations are arbitrarily selected. By contrast, the *repeatability* is the difference between successive measurements carried out by the same measurement operator, or the difference between measurements performed in the same point. The repeatability is therefore more related to the spatial variation of SPL around the area where the measurement is performed, and to the quality of the measurement device.

When subjective noise exposure in rooms is assessed by measurements, it is not useful to use random measurement locations but specific selected locations proposed by the room user. Therefore, the knowledge of reproducibility is of no interest for such a measurement method. Instead, the knowledge of repeatability is important to estimate the measurement uncertainty.

Some national standard measurement methods attempted to minimize the SPL uncertainties at low frequencies including limitations for the

measurement locations. Simmons [6] compared altogether 24 published measurement methods including specifications for LFN measurements. The spatial variation of SPL was measured in 10 different rooms along grids of equally distant points at certain heights. Each method was tested in each room by means of specific instructions on where to put the microphones. The variation of SPL within a method between different sets of measurement locations was found to be unacceptable. The reproducibility was in order of 15 dB at low frequencies. The arithmetic averaging increased the uncertainty. Methods, which performed measurements in the geometrical corners, improved the reproducibility.

Pedersen et al. [7] introduced recently a new method designed for LFN measurements, the 3D corner method. This procedure measures the SPL in four three-dimensional room corners with a maximum distance to the room boundaries of 0.1 m. This aims to find the highest SPL in the room with a high reproducibility. The measured levels are power averaged, and then reduced by 4 dB. The resulting value was considered to describe the perceived noise level in the room. The new method was tested together with the Swedish [8] and Danish [9] methods, in a similar way as done previously by Simmons, in 3 different rooms with 4 different low frequency signals of which 2 were narrow-band and 2 were wide-band. They reported the 3D corner method to have a better reproducibility than the previous methods.

A short description of some existing measuring methods, as compiled by Pedersen et al. [7], is included here. The methods are resumed in Table 1. The 3D corner method, and the new method proposed in this paper are also included.

SP INFO 1996:17 (Sweden) [8]. Measurements are performed in 1/3-octave bands between 31.5 and 200 Hz. SPL is measured and averaged from three positions. Two positions are representative ear positions in normal usage of the room. Distance to adjoining walls should be larger than 0.5 m and height must be 0.6, 1.2 or 1.6 m. Positions around 1/4th, 2/4th and 3/4th along the room length or width is avoided. The C-weighted equivalent SPL is measured in each corner 0.5 m from the walls. The third measurement is performed in the corner with the highest C-weighted SPL.

Nr. 9 1997 (Denmark) [9]. Measurements are performed in 1/3rd octave bands from 5 to 160 Hz. Level is measured and averaged from three positions. Two positions are taken at height 1.0 to 1.5 m, at least 0.5 m from walls, never in the geometrical centre of the room, and representing usual occupant locations. Annoyed occupant should preferably indicate them. The third point is any arbitrary corner. Distance to the adjoining walls must be 0.5-1.0 m.

ISO 16032 [10]. Measurements are performed simultaneously in A- and C-weighting networks in 1/1 octave bands, between 31.5 Hz and 8 kHz. Three measurement locations are used as in the Swedish method. No attention is given to the occupant use of the room, only minimum distances to walls and objects and height above the floor are stated. The C-weighted SPL is measured in each corner 0.5 m from the walls and above the floor. The third measurement is performed in the corner with the highest C-weighted SPL.

DIN 45680 (Germany) [11] and ÖNORM S 5007 (Austria) [12]. Measurement range is 10 - 80 Hz and only one measurement is performed. The measurement point is selected without restrictions.

NSG 1999 (Netherlands) [13]. Measurements are done in 1/3rd octave bands, between 20 and 100 Hz, at single locations. The occupant chooses the measurement locations. Otherwise, they are arbitrarily selected from the corners, with a distance to walls ranging from 0.2 to 0.5 m.

Japanese guidelines [14] perform measurements in only one measurement point which is appointed by the occupant. Measurements are performed between 10 and 80 Hz.

ANSI S 12.9 Part 1 (USA) [15]. Measurements are performed at multiple microphone positions, and corners are preferred. Distance requirements are not specified.

Asumisterveysohje 2003 [16]. Measurements are done in 1/3-octave bands between 20 and 200 Hz. Measurement locations reflect the normal use of the space. Distance to walls should be at least 1 m. If the SPL measured in different locations differ with each other, the higher values are compared against the target values.

Table 1 Summary of measurement methods as compiled by Pedersen et al. [7]. The method proposed in this report lies on the bottom. Every method performs the measurements in 1/3-octave bands, except ISO 16032 which performs in 1/1-octave bands.

No	Ref.	Country	Number of measurement locations	User or operator locations	Points in corner	Frequency range [Hz]	Minimum distance to walls	Height [m]
1	[8]	Sweden	3	2 user	1 corner	31.5 - 200	0.5	0.6, 1.2, 1.6
2	[9]	Denmark	3	2 user	1 corner	5 - 160	0.5	-
3	[10]	ISO 16032	3	2 user	1 corner	31.5 - 8000	-	0.5, 1.0, 1.5
4	[11]	Germany	1	1 operator	-	10 - 80	-	-
5	[12]	Austria	1	1 operator	-	10 - 80	-	-
6	[13]	Netherlands	1	1 user (or)	(or) 1 corner	20 - 100	0.2 to 0.5	-
7	[14]	Japan	1	1 user	-	10 - 80	-	-
8	[15]	USA	multiple	-	corner	-	-	-
9	[16]	Finland	multiple	user	-	20-200	1.0	-
10	[7]	Pedersen	4	-	corner	-	0.1	0.1
11	This report	Oliva et al.	multiple	user	optional	20 - 10000	0.3	0.6, 1.2, 1.55

2.5 Target values

Most countries have not published informal or compulsory target values for the LFN separately, and the target values are based only on the A-weighted SPL in the audio frequency range. The problem arises when the intrusive noise has a strong low frequency character. In this case, the A-weighted target values are not necessarily exceeded, although the noise is clearly heard. Some countries have taken a step forward introducing special target values for LFN in dwellings, see Table 2 and Figure 3. In Finland, the A-weighted SPL caused by external noise sources inside dwellings and schools shall be below 35 dB at day-time and below 30 dB at night-time (VNP 993/92 [17]). If the noise has a low frequency character the measured SPL is compared against the low frequency target values [16]. A procedure, where both the A-weighted

SPL and the low frequency SPLs are considered in parallel, is becoming common in some countries. However, the frequency range and the target values differ between countries. Most defined the maximum acceptable level at night-time and permit a relaxation of 5 dB at day-time. It would be constructive to have both harmonized measurement method and harmonized target values.

Table 2 Maximum allowed SPL inside dwellings at low frequencies in some countries. The hearing threshold [2] is included.

Frequency [Hz]	ISO 226 threshold [dB]	Sweden [dB]	Netherlands [dB]	Poland [dB]	Germany DIN 45680 Lnt [dB]	Denmark infrasound 85 [dB(G)]	Denmark 20 [dB(A)]	Finland [dB]	Moorhouse Proposed [dB]
6.3						77.0			
8						81.0			
10			92.0	80.4	95.0		90.4		87.0
12.5			88.0	73.4	86.5		83.4		82.0
16			84.0	66.7	79.0		76.7		78.0
20	78.5		74.0	60.5	71.0		70.5	74.0	69.0
25	68.7		64.0	54.7	63.0		64.7	64.0	59.0
31.5	59.5	56.0	55.0	49.3	55.5		59.4	56.0	51.0
40	51.1	49.0	46.0	44.6	48.0		54.6	49.0	44.0
50	44.0	43.0	39.0	40.2	40.0		50.2	44.0	38.0
63	37.5	41.5	33.0	36.2	33.5		46.2	42.0	37.0
80	31.5	40.0	27.0	32.5	33.0		42.5	40.0	35.0
100	26.5	38.0	22.0	29.1	33.5		39.1	38.0	33.0
125	22.1	36.0	18.0	26.1			36.1	36.0	31.0
160	17.9	34.0	14.0	23.4			33.4	34.0	29.0
200	14.4	32.0	10.0	20.9				32.0	
250	11.4			18.6					

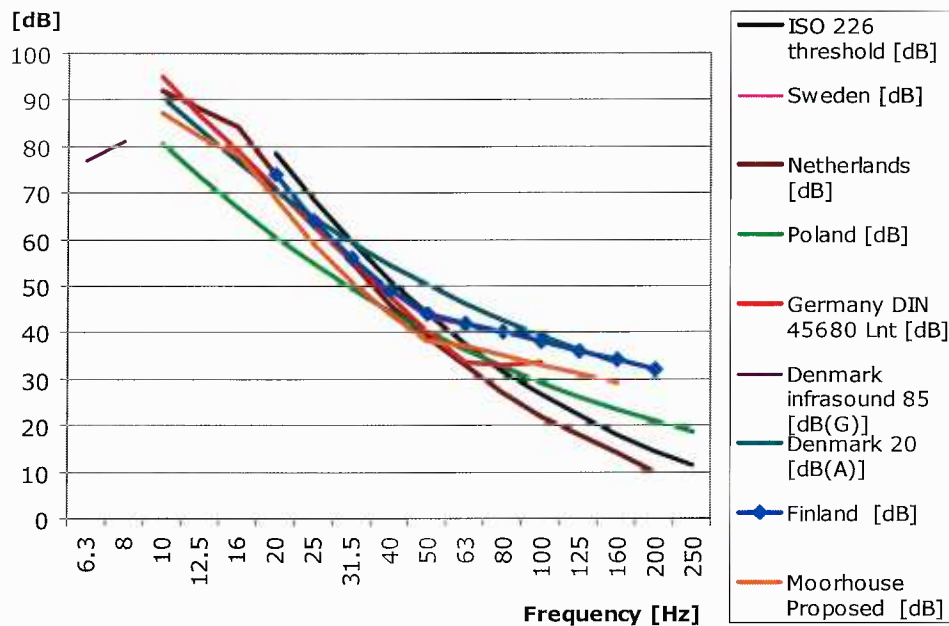


Figure 3 Target values in different countries and threshold of hearing ISO 226:2003 [2].

3 MATERIALS AND METHODS

The experimental part of the project aimed to solid understanding about the distribution of low frequency noise inside enclosures, what is the location of the maximum and minimum SPLs, what is the variation of SPL, and how different parameters, like dimensions of the room, amount of fittings and absorption, affect the spatial variation of SPL. Experimental methods and modelling methods were applied. Those are described in the following.

3.1 Experimental methods

Sound pressure level measurements were performed in five different Case rooms described in Table 3. All measurements were performed in 1/3-octave bands with a sound level meter B&K 2260.

In Cases 2 and 4, the external sound source was a real industrial noise source. In Cases 1, 3 and 5, artificial sound source was used to create the test sounds. Case 3 was an empty and large reverberant room where also Finite Element modelling was done. The other rooms are typically furnished rooms.

Table 3 The descriptions of the five Case rooms, their dimensions, volumes and lowest resonance frequencies calculated according to Eq. (1).

Case	Type of room	Location	Lx [m]	Ly [m]	Lz [m]	Volume [m ³]	Resonance mode (<i>lmn</i>) and corresponding resonance frequency [Hz]										
							100	010	001	110	101	011	200	020	002	111	
1	Office room	Turku	4.7	3.4	2.8	45	37	51	61	62	72	80	73	101	123	88	
2	Dwelling	Vaasa	7.6	6.6	2.5	125	23	26	69	35	72	74	45	52	138	77	
3	Reverberant room	Turku	7.5	4.9	5.2	191	23	35	33	42	40	48	46	70	66	53	
4	Dwelling	Karhula	3.5	2.9	2.4	24	49	59	72	77	87	93	98	119	143	105	
5	Dwelling	Yläne	4.8	2.7	2.3	30	36	64	75	73	83	98	72	127	150	105	
6	small room	Comsol	6	3.5	2.5	53	29	49	69	57	75	85	57	98	138	89	

3.1.1 Case 1: Office room

Measurements were performed in the premises of the FIOH in Turku, Figure 4. Pink noise was created in a meeting room, travelled through the inner yard, and entered into the office room through two opened windows. Windows (75 x 115 cm) were left open to ensure that the SPL of the noise source was higher than the background SPL. The sound source was not located inside the room since the situation where a plane source is causing the sound, i.e. facade or window, was desirable. A point source may induce the room modes differently than a plane source.

The office comprised furniture, like wardrobes, a table and a chair, and 5 cm thick absorptive acoustic panels in a wall and the roof (total panel area 8 m²). Other surfaces were hard. Measurements were done along a grid of 7 x 10 equidistant points at 1.2 m and 1.5 m heights. Distance between locations was approximately 0.5 m. Measurements were also performed in all corners at the floor and roof level 10 cm from every surface belonging to each corner.



Figure 4 Left) Inner yard in Case 1. The locations of the source and measurement rooms are indicated. Right) Photo of the office room. The opened windows are shown behind.

3.1.2 Case 2: Dwelling 1

The measurement place was a dwelling in the city of Vaasa. The noise source was the exhaust pipe of a power plant. The locations of the sound source and of the dwelling are shown in Figure 5-left. The distance between them was about 200 m. Noise entered the living room mainly through the windows which was shown by sound intensity measurements. The sketch of the living room and the location of the measurement locations are shown in Figure 5-right. The measurements were performed in all corners at the floor and roof level keeping a constant distance of 10 cm from every surface belonging to each corner. Measurements were also done in the typical occupant locations, i.e. sofa, and in some locations in the middle of the room. Furniture was typical of living rooms.

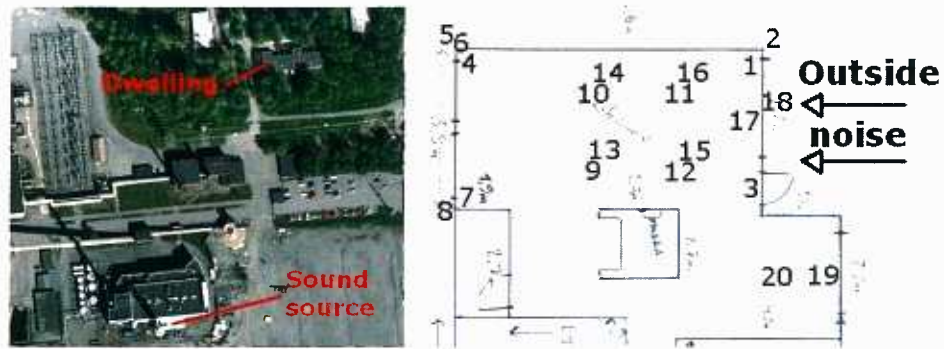


Figure 5 Left) Air photo of Case 2. The locations of the sound source the and dwelling are indicated. Right) Floor plan of the living room from Case 2. The measurement locations are shown.

3.1.3 Case 3: Reverberant room

The reverberant room is located in the premises of the FIOH in Turku. LFN was created in the nearby room and transmitted inside the measurement room through an opening of 0.6 x 1.0 m in the wall. The sound source (opening) was like a plane sound source. The measurements were performed over a grid of 16 x 11 points at 1.5 m