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TITLE

Low frequency sound and vibration insulation in buildings

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Forsvarsbygg

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ABSTRACT

This report is based on presentations and discussions in a workshop and meetings with participants from Chalmers University of Technology, Forsvarsbygg, Norwegian Geotechnical Institute (NGI), Norwegian University of Science and Technology (NTNU), and SINTEF.

The report gives a summary of a literature search that was conducted as part of the project.

The report also gives an overview of low frequency noise (LFN) and vibration impact on humans, and lists relevant national and international standards and regulations.

Problems and challenges with respect to measurements of LFN and vibration in buildings and sound and vibration insulation at low frequencies have been discussed.

A list of items for further studies has been proposed.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Acoustics	Akustikk
GROUP 2	Vibrations	Vibrasjoner
SELECTED BY AUTHOR	Sound insulation	Lydisolasjon
	Low frequency noise	Lavfrekvent støy

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Truls Gjestland

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June 2006

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Appendix

1 Introduction

Low frequency sound and vibration insulation in buildings is a complex issue. The phenomena that governs the insulation properties are only partly known. Theoretical models are almost non-existing, and knowledge about practical methods for sound insulation at very low frequencies are of a meagre and unsatisfactory kind.

Existing building codes and regulations seldom address sound components below about 50 Hz, even though noise and vibration at lower frequencies can cause considerable annoyance.

Forsvarsbygg (The Norwegian Defence Estates Agency) has initiated a pilot study to address problems concerning low frequency sound insulation in buildings. This study has been a cooperation between the following research institutions: Chalmers, NTNU, NGI, and SINTEF.

This report sums up the results from a workshop and several meetings held in connection with the pilot study.

In accordance with common international practice, the abbreviation LFN, low frequency noise, will be used in this report to denote sounds with frequency components below about 100 Hz.

2 Experiences from case studies in Norway

In recent years there has been an extensive focus on sound insulation against outdoor transportation noise in Norway. This is mainly due to the implementation of new regulations which forces transportation authorities to improve façade insulation if the indoor level exceeds 42 dB, (24 hour A-weighted equivalent level). The main focus has been on traditional sound insulation above 100 Hz. Thus not much has been done concerning the lower frequency range.

A few field studies, however, have been carried out with some emphasize on LFN. In 1998 a test building at a military training site was examined and reinforced to deal with noise from a combat vehicle (Leopard), with a noise spectrum dominated by a pure tone at approximately 80 Hz. This is referred to as the Asprusta case. In 2003-2004 measurements were carried out to assess indoor noise and vibration levels, sound insulation and insulation improvement, in a building close to a military airport. This is referred to as the Gildeskålveien case. The dominating sound source in this case is the F-16 fighter aircraft at takeoff. In addition a number of sound insulation measurements exist for building façades in connection with sound proofing projects around a few airports. In 1992-93 investigations on LFN and vibration were performed in the community around Lista air-force base. Further investigations were performed in 2000-2001 as part of a lawsuit against Forsvarsbygg from neighbours claiming building damage due to LFN and vibration.

There has also been increased focus on building vibration after the new building regulation (Forskrift til Plan- og bygningsloven) was issued in 1997, where vibration requirements are specifically mentioned.

The different field studies are reported elsewhere (Solberg et al. 1999, Cleave et al. 2004 and Madshus et al. 1993/2000). Results from these studies are pointed out here to illustrate some of the challenges dealing with LFN and vibration in practical matters.

2.1 The Asprusta case

The Asprusta building was located within the Rødsmoen/Rene military training ground, and was used as a test object for insulation against LFN from combat vehicles . The case is interesting because it illustrates challenges of adding weight to traditional lightweight wooden building constructions, as a means to increase sound insulation. The effects are measured in a frequency range down to 50 Hz. As can be seen in Figure 2-1 a good sound proofing result in one room is no guarantee for the same result in another, even though the rooms are in the same building, are fairly similar and are exposed to virtual identical treatment.

The building was an abandoned dwelling and is now demolished.

2.2 The Gildeskålveien case

In 2003 and 2004 measurements of vibration and LFN were made in a typical two storey Norwegian wooden single family house. The house was situated in Gideskålveien near Bodø airport, with F16 take-offs used as the sound source. Between the two sets of measurements several improvements were made to the sound insulation of the house: the external walls were fitted with an extra exterior lining as shown in Figure 2-2 , better insulation was installed in the ceiling of the upper storey, and the windows were upgraded to today's standard. The measured vibration was the result of LF noise pressure acting on the building.

The measurements were done throughout the whole frequency range down to 1 Hz. It illustrates the effects of traditional sound proofing like window replacements and wall reinforcements in lightweight wooden dwellings. In Figure 2-3 we see a clear positive effect above 100 Hz due to new windows, reinforcement of the wall constructions, and treatment of ventilation openings. At 100 Hz, however, the effect of the treatment is negative because a stiffer wall construction has caused a resonance at 80 Hz to be shifted up towards 100 Hz. In the range below 100 Hz the insulation is dominated by a large variety of resonance phenomena, causing the values to raise and drop rapidly. Even though there are large uncertainties in these measurements, the figure gives a good example of what levels of sound insulation to expect in this frequency range. It also illustrates that sound insulation measures with good effect at higher frequencies may very well have no effect, or even negative effect, at low frequencies.

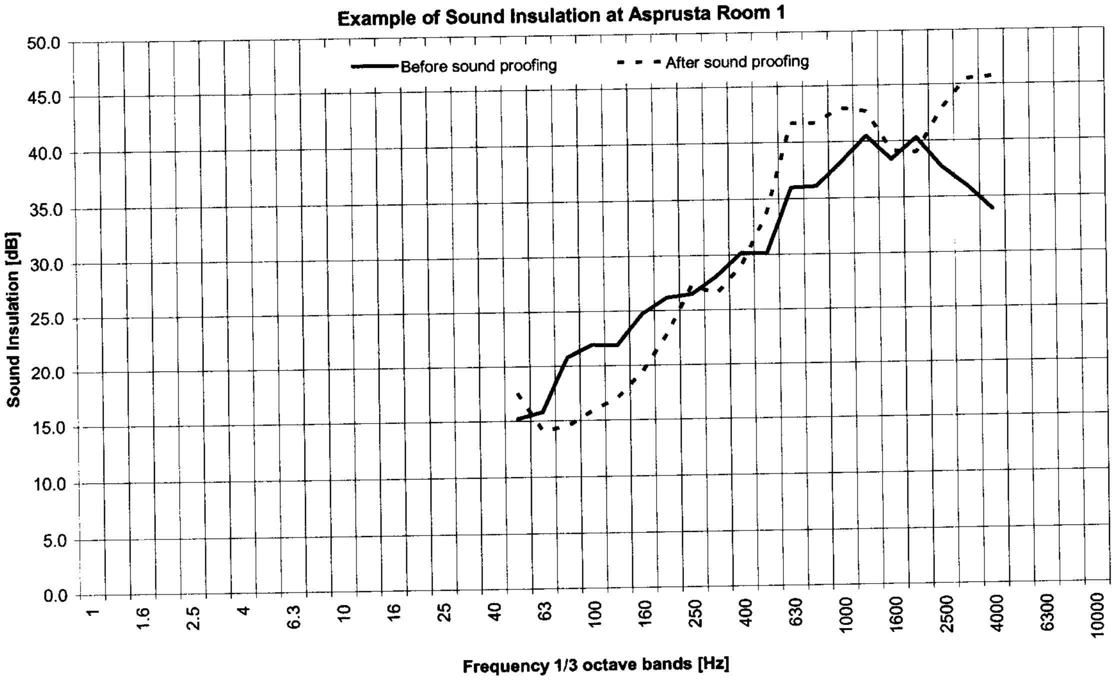
Both the sound and the vibration were lower after the building improvements, but, as shown in Table 2-1, there was no measured improvement in the low frequency sound insulation, and a worsening in the low frequency vibration insulation in the first floor (Level 1). The difficulties in measuring LFN, mentioned in this report, have certainly contributed to the uncertainty in these results, as the uncertainty of the improvement increased with decreasing frequency. The first measurements gave indoor LFN and vibration which exceeded common acceptance criteria for both noise and vibration.

Table 2-1 Sound and vibration insulation 'improvement' in Bodø
(See chapter 5 for comments on uncertainties)

Location	Insulation type	Frequency range [Hz]	Insulation improvement
Level 1	Vibration	10-20	5 dB worse
		20-80	5-10 dB improvement
	Sound	20-100	No improvement
		100-2000	2-6 dB improvement
Level 2	Vibration	8-20	5 dB improvement
		20-80	No substantial improvement
	Sound	20-600	No improvement
		600-2000	2-14 dB improvement

Sound insulation against exterior LFN in general is dominated by a large number of resonance effects. To understand and master the challenges in this field is pretty much a question of being able to control and manage these resonances. This issue is discussed later in this report.

The apparently different results for the two experiments must, however, be discussed with reference to the measurement methods and the measurement uncertainty. There are no standardized methods for building acoustic measurements below the 1/3 octave centred at 50 Hz, and the uncertainties can be rather large, see Chapter 6.



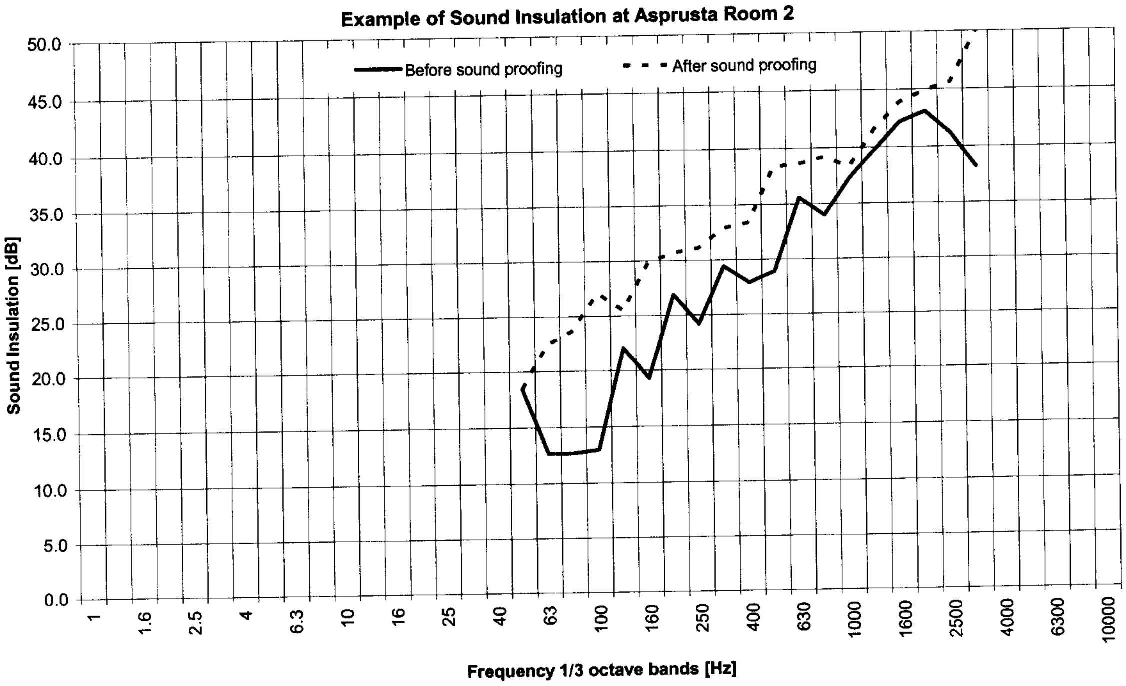
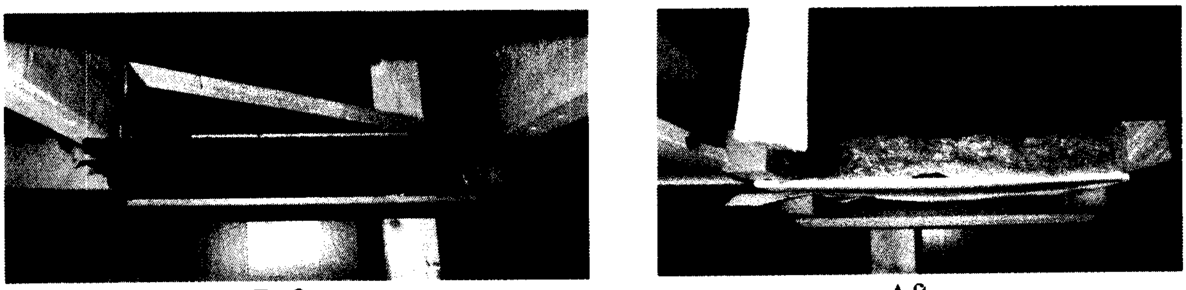


Figure 2-1 Examples of successful (lower diagram) sound proofing of a lightweight wooden facade, and unsuccessful (upper diagram) result of the same measure. The curves apply to two different rooms in the same building both improved by adding light concrete to exterior lining.



Before After

Figure 2-2 Exterior wall insulation improvement, Gildeskålveien, Bodø

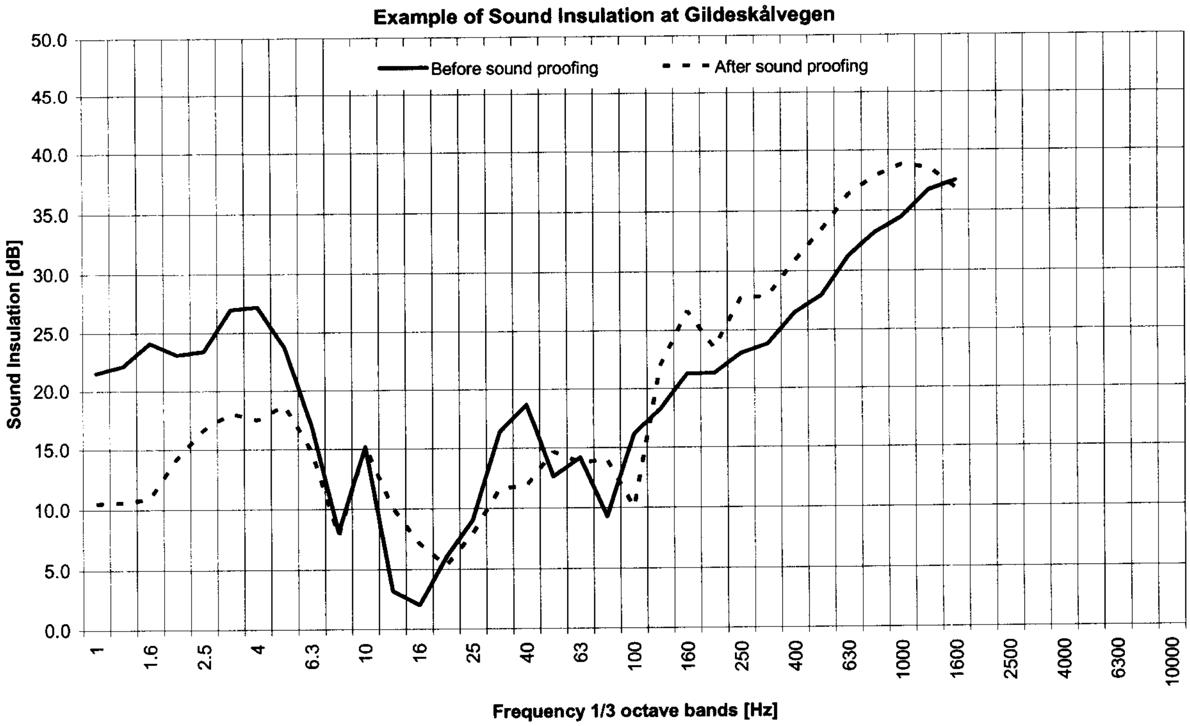


Figure 2-3 Example of traditional soundproofing against aircraft noise in light weight dwelling construction

2.3 The Lista case

The Lista case deals with LFN and building vibration from military blast activity. The case is interesting in the respect that LFN and low frequency vibration impact on a whole community has been measured and analysed, and that a large portion of involved people have expressed their opinion on the impact. This was done in the lawsuit against Forsvarsbygg. Even though building damage postulated to be caused by the noise and vibration was the subject of the lawsuit, people expressed that what mostly annoyed and bothered them was building vibration and rattling, not the audible LF blast noise itself. This is in agreement with results from a statistical analyses of all blasts during a typical year, as shown in Figure 2-4. The analyses show that common criteria for indoor vibration (NS 8176) are more frequently exceeded than corresponding criteria for LFN (Rylander et al. 1996).

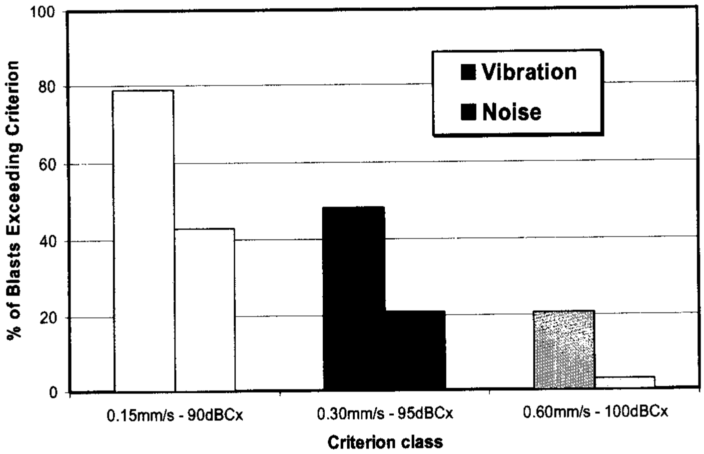


Figure 2-4 Lista: Analyses of all blasts during one year of operation, total 314 blasts ranging from 0.1 to 88 kg TNT-equivalent. Percent of blasts exceeding representative outdoor LFN criteria and corresponding indoor LF-vibration criteria at a typical residence. Results indicate that annoying vibration is a more frequent community impact than annoying noise.

3 Literature on low frequency noise (LFN), infrasound and vibration

A literature search was conducted partly based on a regular WEB search, and partly based on information and suggestions from our international network of colleagues.

The main literature data base that was accessed was: Science citation index.
http://portal.isiknowledge.com/portal.cgi/portal.cgi/?Init=Yes&SID=W1MCif2hLc9kgPGBJMm

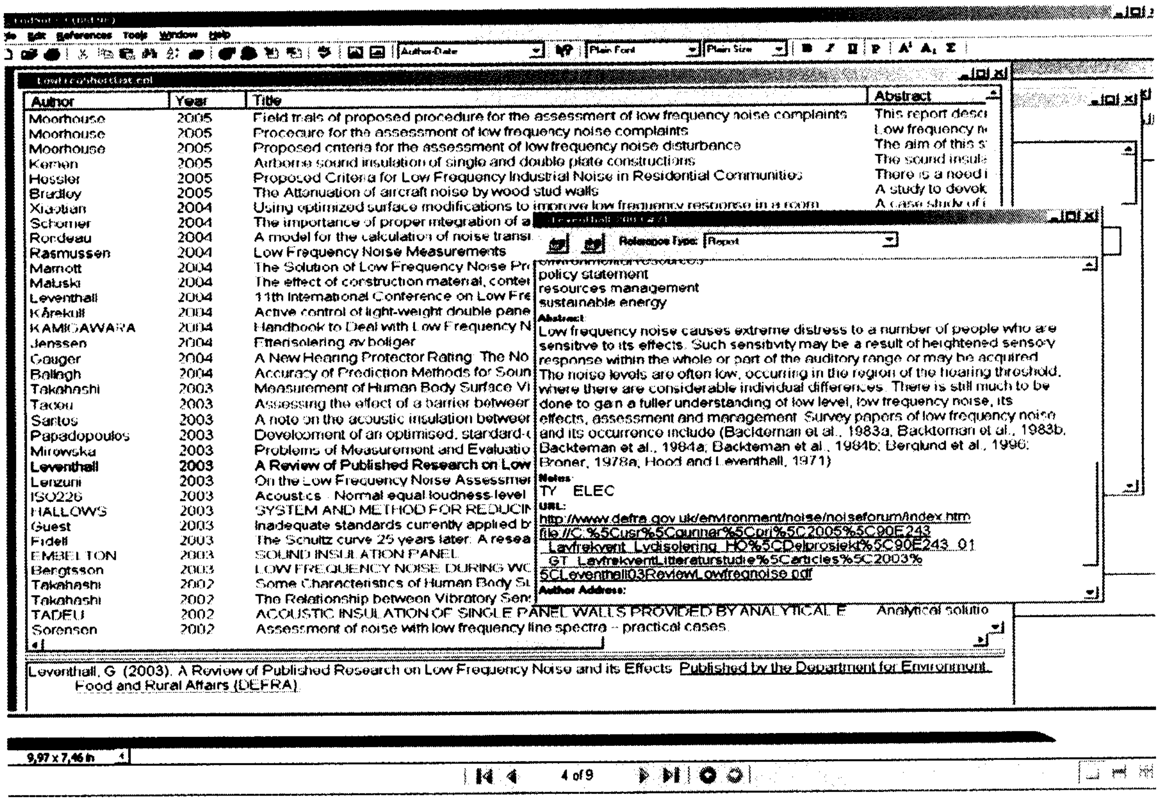
Other data bases comprise:
- National technical information service: http://www.ntis.gov.
- National physical laboratory: http://www.npl.co.uk/acoustics/publications/.
- IngentaConnect: http://www.ingentaconnect.com/.
- Scirusis: http://www.scirus.com.

We also search relevant internationally renowned journals:
- Journal of the Acoustical Society of America
- Journal of Sound and Vibration
- Applied Acoustics
- Journal of Low Frequency Noise
- Noise Control Engineering Journal

and relevant PhD thesis on LFN and related subjects.

3.1 Results

1. Current collection of 133 pdf-files (see figure next page)
2. A database with references. (see figure next page)
3. A short list with some of the more relevant references (see appendix).



Author	Year	Title	Abstract
Moorhouse	2005	Field trials of proposed procedure for the assessment of low frequency noise complaints	This report desc
Moorhouse	2005	Procedure for the assessment of low frequency noise complaints	Low frequency n
Moorhouse	2005	Proposed criteria for the assessment of low frequency noise disturbance	The aim of this s
Kernen	2005	Airborne sound insulation of single and double plate constructions	The sound insul
Hessler	2005	Proposed Criteria for Low Frequency Industrial Noise in Residential Communities	There is a need i
Bradley	2005	The Attenuation of aircraft noise by wood stud walls	A study to devel
Xiaojian	2004	Using optimized surface modifications to improve low frequency response in a room	A case study of i
Schomer	2004	The importance of proper integration of a	
Rondeau	2004	A model for the calculation of noise transı	
Rasmussen	2004	Low Frequency Noise Measurements	
Marriott	2004	The Solution of Low Frequency Noise Pr	
Maluski	2004	The effect of construction material, conte	
Leventhall	2004	11th International Conference on Low Fre	
Kårekull	2004	Active control of light-weight double pane	
KAMIGAWARA	2004	Handbook to Deal with Low Frequency N	
Jenssen	2004	Etterisolering av boliger	
Gauger	2004	A New Hearing Protector Rating: The No	
Balingh	2004	Accuracy of Prediction Methods for Soun	
Takahashi	2003	Measurement of Human Body Surface Vi	
Tadeu	2003	Assessing the effect of a barrier betweer	
Santos	2003	A note on the acoustic insulation betweer	
Papadopoulos	2003	Development of an optimised, standard-(	
Mirowska	2003	Problems of Measurement and Evaluatio	
Leventhall	**2003**	**A Review of Published Research on Low**	
Lenzuni	2003	On the Low Frequency Noise Assessmer	
ISO226	2003	Acoustics Normal equal-loudness-level	
HALLOWS	2003	SYSTEM AND METHOD FOR REDUCIN	
Guest	2003	Inadequate standards currently applied b	
Fidell	2003	The Schultz curve 25 years later: A resea	
EMBELTON	2003	SOUND INSULATION PANEL	
Bengtsson	2003	LOW FREQUENCY NOISE DURING WC	
Takahashi	2002	Some Characteristics of Human Body Su	
Takahashi	2002	The Relationship between Vibratory Sen	
TADEU	2002	ACOUSTIC INSULATION OF SINGLE PANEL WALLS PROVIDED BY ANALYTICAL E	Analytical solutio
Sorensen	2002	Assessment of noise with low frequency line spectra – practical cases.	

Leventhall, G. (2003). A Review of Published Research on Low Frequency Noise and its Effects. Published by the Department for Environment, Food and Rural Affairs (DEFRA).

Reference Type: Report

policy statement
resources management
sustainable energy

Abstract:
Low frequency noise causes extreme distress to a number of people who are sensitive to its effects. Such sensitivity may be a result of heightened sensory response within the whole or part of the auditory range or may be acquired. The noise levels are often low, occurring in the region of the hearing threshold, where there are considerable individual differences. There is still much to be done to gain a fuller understanding of low level, low frequency noise, its effects, assessment and management. Survey papers of low frequency noise and its occurrence include (Backteman et al., 1983a, Backteman et al., 1983b, Backteman et al., 1984a; Backteman et al., 1984b; Berglund et al., 1996; Broner, 1978a; Hood and Leventhall, 1971)

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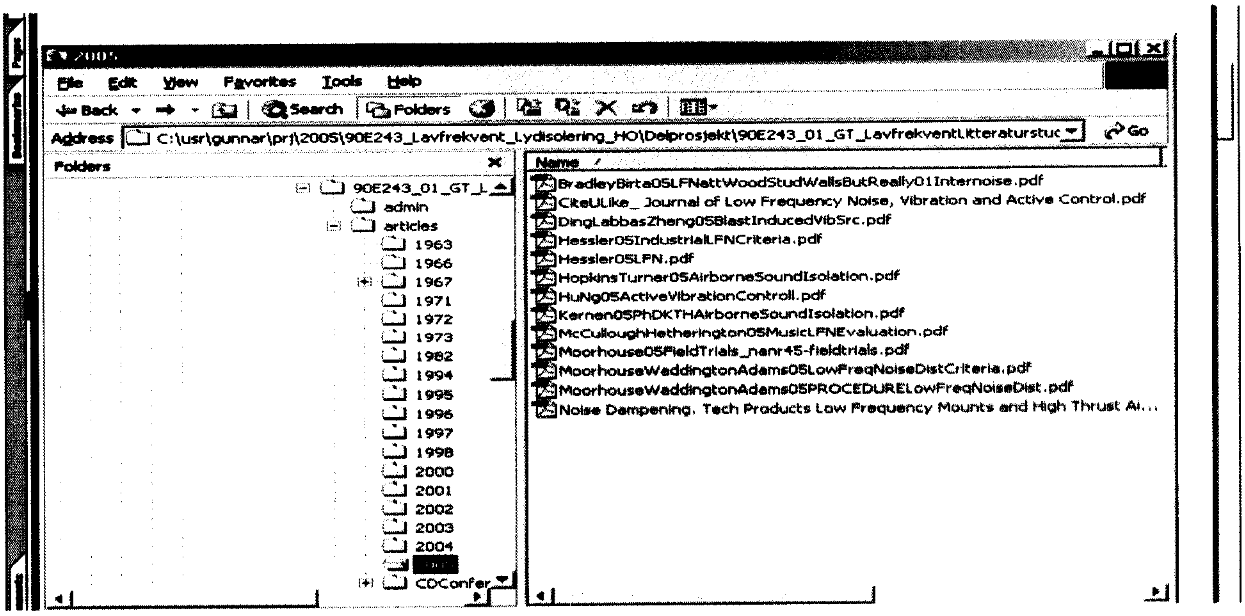

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- Noise Dampening. Tech Products Low Frequency Mounts and High Thrust Ai...

4 Perception of LFN, infrasound, vibration and rattle

Military activity like heavy weapons shooting, blasts and aircraft operation produce considerable low frequency sound pressure in the frequency range from 100 Hz down to a few Hz. The sound pressure will as a secondary effect act on buildings and the surrounding ground and cause vibration and rattling in addition to the audible / sensible sound.

A person with normal hearing can perceive sound signals at frequencies down to approximately 20 Hz. The frequency response of the human auditory system is highly un-linear in the sense that as the frequency is decreased, a steady increasing sound pressure level is required in order to produce the same auditory sensation (loudness). The hearing threshold at 100 Hz is about 50 dB lower than the threshold at 20 Hz.

Similarly the dynamic range of the hearing decreases towards lower frequencies, that is the range between the hearing threshold and the level above which the hearing sensation changes from "sound" to "pain". At 100 Hz the dynamic range is approximately 100 dB, and at 20 Hz the range is reduced to about one half, 50 dB. Sound at frequencies below 20Hz is termed infrasound.

In addition to causing a normal hearing sensation, low frequency noise (LFN) also affects the human body in other ways. At frequencies below 20 Hz and high sound pressure levels (> 130 dB), the pressure balance between the outer and the middle ear can be distorted. The pressure is usually equalized via the Eustachian tube, but high level LFN can cause a pressure drop in the middle ear. This will cause a sensation of sharp pain in the tympanic membrane. LFN at similar sound pressure levels can cause balance disorders and vertigo.

At higher levels of LFN cardiovascular effects can be observed (>150 dB), and at still higher levels (>165 dB) the respiratory function is affected.

High sound levels causes an upward masking that may affect the intelligibility of speech. This effect can be observed for LFN levels above approximately 115 dB.

At ultra low frequencies, 5 Hz and below, sound pressure levels above 120 dB may cause general discomfort. It is not clear if such signals are perceived via the auditory system, the balance organ or via an other sensory path.

LFN is often associated with vibration and rattling that can add to the negative impact of the sound itself. Vibration and rattling in buildings is caused by LF sound pressure acting on the building, on building elements and on the ground near the building.

A person will sense vibration by its whole body over the frequency range from about 1 Hz to 80 Hz. The sensitivity is fairly independent of frequency down to about 10 Hz, from where it drops off towards the lowest frequencies (vibration is rated as particle velocity). The reaction to whole body vibration and infrasound is among the humans deeply inherited, "newer sleeping" warning systems for disasters like earthquakes, volcanoes, landslides, gales and tsunamis. They evoke physiological preparedness mechanisms and therefore tend to be annoying, even if only slightly exceeding the threshold of perception. The annoyance tends to be more of the "on/off" type than for audible sound. There is also a tendency that the number of events is not very important for the annoyance. Most animals are even more sensitive to vibrations than humans.

Experience indicates that neighbor complaints to low frequency military noise often relate to building vibration and rattling rather than to the audible noise itself. Building vibration may also disturb farm animals and disrupt operation of sensitive equipment. In extreme cases, air pressure and vibration may lead to building damage.

Military buildings and military personnel close to firing positions may be exposed to high levels of vibration that may have health implications.

Rattling is a secondary effect of building vibration and LFN Smaller elements like doors, windows and inventory are put in motion and create rattling and quirking sounds, often also associated with visual impression of vibration. These effects, in addition to the low frequency audible sound and whole body vibration will increase the impact.

5 Regulations

5.1 National and international regulations on LFN

Some countries have recommendations and guidelines regarding LFN. It has been difficult to assess the legal status of these recommendations, but in most cases they seem to be advisory, in other words: if the sound levels are kept below the proposed criteria, LFN complaints are not likely to occur.

ISO 7196 defines a special weighting curve for LFN, the so called G-weighting. This function has a maximum around 20 Hz. The slope is -18 dB/oct for higher frequencies and 12 dB/oct for frequencies between 1 Hz and 20 Hz. If all the energy of a signal is concentrated at 20 Hz, the G-weighted level is 10 dB higher than the linear (un-weighted) value.

5.1.1 Sweden

Sweden has special recommendations for LFN in the frequency region 31.5 – 200 Hz, (Socialstyrelsen, 1996). The noise shall be assessed in 1/3 octave bands and the sound levels shall not exceed the values in Table 5-1 for any one of the 9 frequency bands.

Table 5-1 Sweden. Maximum acceptable1/3 octave levels for LFN

Hz	31.5	40	50	63	80	100	125	160	200
dB	56	49	43	41.5	40	38	36	34	32

5.1.2 Denmark

Danish regulations calls for an A-weighting of the sound levels in the frequency bands 10 - 160 Hz. The measured 1/3 octave bands are A-weighted and summed to give a “low frequency A-weighted level”, $L_{pA,LF}$. This value is compared with limit values for various locations. The Danish recommendations also calls for a 5 dB penalty for impulsive sounds (Orientering fra Miljøstyrelsen, nr 9, 1997).

Maximum acceptable levels for $L_{pA,LF}$

dwellings, evening and night, 1800 – 0700	20 dBA (85 dBG)
dwellings, daytime, 0700 – 1800	25 dBA (85 dBG)
offices, classrooms	30 dBA (85 dBG)
other work rooms	35 dBA (90 dBG)

There are no specific reference curve, but the Danish recommendations can be compared with other criteria, assuming that all the low frequency energy is concentrated within one single 1/3 octave. In practice this extreme situation seldom arise, and the assumption gives values that are artificially high. Table 5-2 gives maximum acceptable levels for dwellings during the evening/night period.

*Table 5-2 Denmark. Maximum acceptable 1/3 octave levels for LFN**

Hz	*10*	*12.5*	*16*	*20*	*25*	*31.5*	*40*	*50*	*63*	*80*	*100*	*125*	*160*
dB	*90.4*	*83.4*	*76.7*	*70.5*	*64.7*	*59.4*	*54.6*	*50.2*	*46.2*	*42.5*	*3.1*	*36.1*	*33.4*

**recommendations for dwellings (evenings and nights). All energy in 1/3 octave*

According to the Danish ministry of the environment the LFN recommendations are enforced by local authorities, and yearly complaint rate is between 1 and 10 per one million inhabitant, in places where the recommendations are followed. This indicates that the criteria are relatively strict. A special Danish publication deals with LFN in the environment

A new recommendation for occupational noise (AT-vejledning D.6.5, Nov 2004) uses the G-weighting (ISO 7196) for assessing LFN. The limit for occupational exposure is set at a 95 dB (G-weighted) for a normal working day, 8 hours. This corresponds to a linear level of 85 dB at 20 Hz, which again is only 6.5 dB above the hearing threshold. Slightly higher levels may be tolerated if there are audible noise at higher frequencies. Infrasound is considered to be less annoying if the person is also exposed to audible noise. For exposure to short events of LFN, a G-weighted level of 100 – 105 dB is acceptable.

5.1.3 The Netherlands

The Dutch method for assessing LFN is based on audibility only, and nuisance or annoyance is not considered (NSG – Richtlijn Laagfrequent Geluid). The reference curve coincide with the hearing thresholds for the 10 % most sensitive people in an otologically unselected population aged 50-60 years old. These thresholds are typically 4-5 dB lower than the average threshold for "normal young adults" aged 18 – 25 as specified by the standard ISO 226.

The assessment of LFN is limited to the frequency range 20 – 100 Hz, see table 4.3.

Table 5-3 The Netherlands. Maximum acceptablel/3 octave levels for LFN

Hz	20	25	31.5	40	50	63	80	100
dB	74	64	55	46	39	33	27	22

A recent Dutch study indicates that as much as 15 percent of the Dutch population are annoyed by LFN including LFN from neighbors. The number of complaints, however, are relatively few. A reason for this may be that the environmental authorities in most countries can not handle complaints of low-frequency noise especially from private neighbors.

5.1.4 Germany

Germany uses two assessment methods for LFN depending on the tonality of the signal (DIN 4560/45680, 1997). A signal is considered "tonal" if the level in one frequency band exceeds the levels in the two neighboring bands by more than 5 dB. For tonal noise 1/3 octave levels for the frequency range 8 – 100 Hz are compared with the criterion given in Table 5-4 table 4.4. The noise is considered a nuisance during the night period if the values in Table 5-4 table 4.4 are exceeded. For the day period the values can be exceed by maximum 5 dB in any 1/3 octave band.

Table 5-4 Germany. Maximum acceptable1/3 octave levels for LFN (night time)

Hz	8	10	12.5	16	20	25	31.5	40	50	63	80	100
dB	103	95	87	79	71	63	55.5	48	40.5	33.5	28	23.5

If the noise is non-tonal a day time limit of 35 dB is imposed on the A-weighted equivalent level for the frequency bands 10 – 100 Hz. The A-weighting is obtained by only using the 1/3 octave bands for which the threshold in Table 5-4 is exceeded. The limit for night time exposure is 25 dB.

5.1.5 Poland

In Poland LFN is assessed in the frequency range 10 – 250 Hz. The reference curve is given in Table 5-5.

Table 5-5 Poland. LFN reference curve

Hz	10	12.5	16	20	25	31.5	40
dB	80.4	73.4	66.7	60.5	54.7	49.3	44.6
50	63	80	100	125	160	200	250
40.2	36.2	32.5	29.1	26.1	23.4	20.9	18.6

A specific LFN source is considered annoying if the sound pressure level exceeds the reference curve, and simultaneously exceeds the background noise level by more than 10 dB for tonal noise, and 6 dB for broadband noise.

An ordinance from the Ministry of Labor and Social Policy on “maximum admissible intensity” (1998) specifies a level of maximum 110 dB (linear) for each octave band 4 Hz to 16 Hz and 105 dB at 31.5 Hz in order to have adequate “health protection at all workplaces”. These are equivalent levels for 8 hour exposure. For short time exposure the limit may be raised to 137 dB and 132 dB respectively. For office environments the corresponding limits are 85 dB octave levels 4 Hz-16 Hz and 80 dB for the 31.5 Hz octave.

5.1.6 ISO 226

The international standard ISO 226 defines the hearing threshold for otologically normal young adults, 18 – 25 years of age. This threshold is defined in Table 5-6.

Table 5-6 ISO 226. Hearing threshold for normal young adults

Hz	20	25	31.5	40	50	63	80	100	125	160	200	250
dB	78.5	68.7	59.5	51.1	44.0	37.5	31.5	26.5	22.1	17.9	14.4	11.4

In figure 4.1 the reference curves used in various national criteria are compared with the ISO threshold.

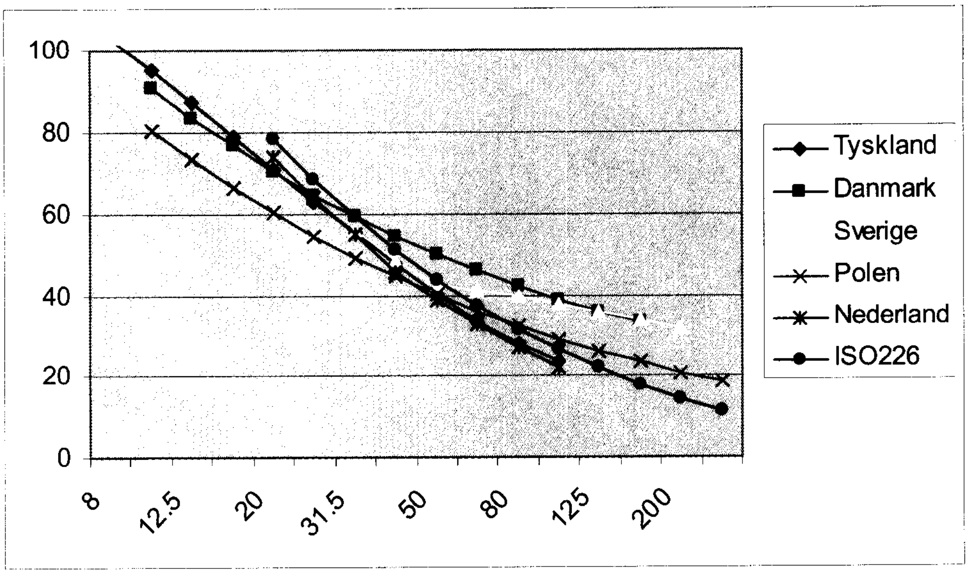


Figure 5-1 Reference curves for assessing LFN

5.1.7 Comparison of regulations on LFN

The various national criteria curves in Figure 5-1 are fairly consistent. It should be noted that the Danish curve is based on a special assumption (all the LFN energy in one 1/3 octave band only), and it is thus not directly comparable with the other ones. The impression that it is higher than the other curves is therefore slightly misleading. Also the Polish curve, which appears to be the lowest one, is to be used together with an extra requirement for the background noise. For this reason the actual threshold is usually closer to the other curves. In total the criteria curves are actually even more in agreement than can be seen from Figure 5-1.

It may seem rather stringent to require that LFN, in order not to be annoying, must be reduced to levels around or below the normal threshold of hearing. However, there is a growing experience in many countries that such low limits are necessary. There seems to be little or no habituation to LFN, and it must be observed that the standard hearing threshold is based on the median. This means that 50 % of the population is more sensitive. About 16 % of the population has a threshold 6 dB or more lower than the standard curve, and national noise criteria are often based on a “ten to twenty percent concept”, for instance “ten percent highly annoyed”.

5.2 National and international regulations on low frequency vibration and rattling

The average vibration sensitivity versus frequency of the human is defined in the international standard ISO 8041. The response weight function for whole body vibration in buildings covers the frequency range from 1Hz to 80Hz. It accounts for the fact that a person may take any posture when in a house; standing, sitting, laying i.e. it is a "combined curve" for all postures. The ISO-curve is reproduced in Figure 5-2. The plotted curve has been converted from acceleration to velocity, which is more convenient for being compared to sound pressure. For comparison the figure also plots the A-, C- and G- weighting functions for sound pressure, extended down to 1Hz. From the plots one can see that the human sensitivity to sound pressure (LFN/infrasound) drops off more rapidly towards low frequency than what is the case for vibration.

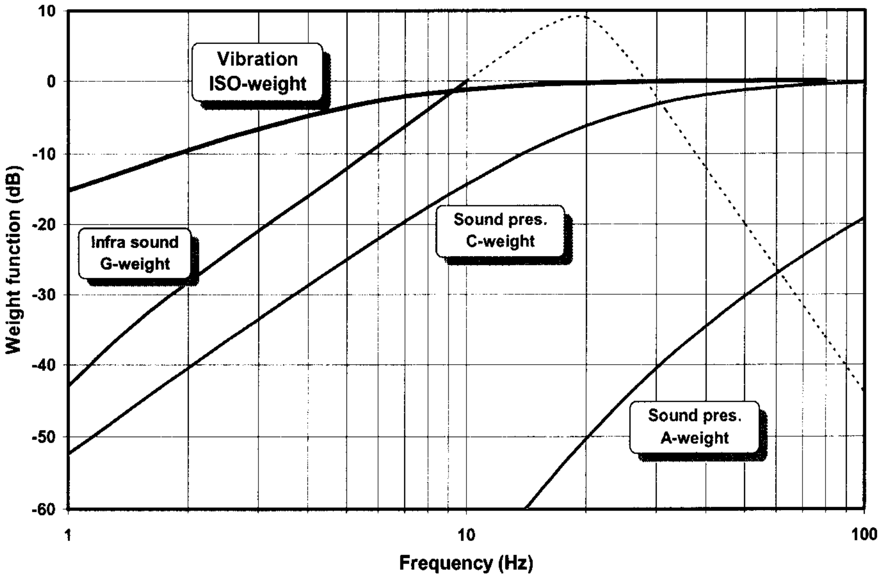


Figure 5-2 Vibration sensitivity weighting function for human exposure to whole body vibration in buildings according to ISO 8041, converted from acceleration to velocity (red curve). For comparison are also shown the sound pressure weight functions A(green curve)-, C-(blue curve) and G-(black curve) in the LFN range 1-100Hz.

The threshold of perception for whole body vibration is typically 0.15mm/s, when weighted with the above curve and averaged over 1s. Roughly this corresponds to a sound pressure of 70 dB if freely radiated from a large vibrating surface. By comparison with Figure 5-1 this indicates that whole body vibration may dominate the perception for frequencies below about 25Hz in a coupled LFN – vibration environment.

ISO 2631-2 specifically treats vibrations in buildings. The standard does, however, not contain criterion values for acceptable vibration, except a general statement that adverse comments regarding vibration may arise when the vibration magnitudes are only slightly in excess of perception level.

The German standard DIN 4150-2 is more specific on vibration criteria for buildings. It uses the same frequency weighting as ISO, but a shorter (125ms) averaging time. For residential areas the acceptance value is 0.15mm/s during day-time and 0.10mm/s during nights. These numbers are stricter limits than if they had been evaluated by 1s averaging. The standard has a scheme to relax the limits for infrequent, short-term vibration events. This scheme may be a useful staring point for establishing vibration criteria for low frequency military sources like heavy weapons shooting and blasting.

An alternative approach to handle infrequent and repeated short-duration vibration exposure is the use of ¼-th power vibration dose value VDV. The approach is mentioned in ISO 2631-1, and elaborated on by Griffin (1990). The method is however controversial, and its relevance for assessing vibration annoyance is not properly documented.

Military personnel may be exposed the high vibration magnitudes, which may have health implications. ISO 2631-1 gives general threshold limit values for vibration. ISO 2631-5 and ISO 13090-1 are more specific for exposure to shock-like vibration.

Some guidance on vibration limit values for sensitive equipment in buildings are found in ISO/TS 10811, however criteria for transient vibration are not well defined.

No national or international regulations are found for house rattling. What is available is mostly related to sonic booms. Figure 5-3 plots the results from psychological testing on annoyance to house rattling due to sonic booms. One should however be careful when using this type of data since building response to sound pressure and particularly rattling varies highly with type and standard of building, inventory and ground condition. There is evidence that rattling causes annoyance at much lower sound pressure levels than those in Figure 5-3, ref. Schomer (1978).

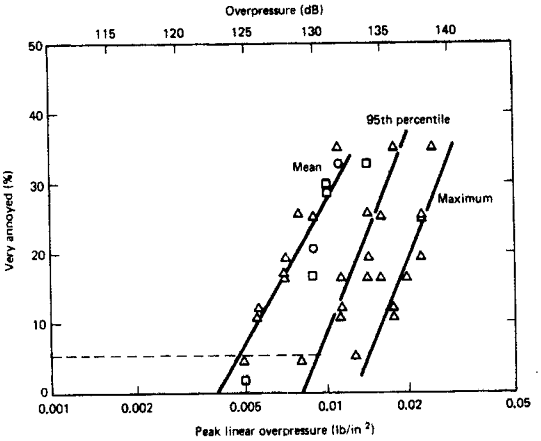


Figure 5-3 Percentage of people "more than moderately annoyed" by a few sonic booms per day based on psychological testing (After Siskind at al. 1980. Same data are found in FAGS-1993)

5.3 The situation in Norway

There are no specific requirements for indoor LFN in Norway. "Sound conditions in buildings", NS 8175, is a standard that regulates the recommended acoustic properties of various types of buildings (residences, offices, schools, etc.). The standard is almost exclusively based on A-weighted levels. Maximum recommended sound levels in residences and hospitals from technical installations are also defined in C-weighted quantities.

The standard NS 8175 refers to other standards that define how relevant parameters shall be measured. These standards limit A-weighted quantities to the 1/3-octave band centered at 63 Hz, and C-weighted quantities to 31.5 Hz. Sounds at lower frequencies are therefore not considered.

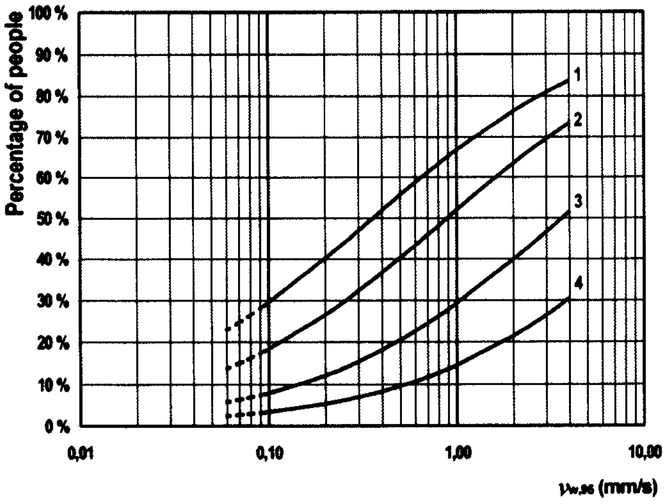
Neither are there any official Norwegian regulations for building vibrations caused by low frequency military sources. The most relevant reference are guideline values for building vibration induced by land based transportation given in the Norwegian Standard NS 8176. The criterion values in this standard are defined as Vibration Classes A through D and are reproduced in Table 5-7 below.

Table 5-7: Recommended building vibration criteria for land-based transportation according to NS 8176

Vibration class	**Description**	**Vibration criterion $v_{w,95}$ (mm/s)**
Class A	Corresponds to very good vibration conditions, where people will only perceive vibrations as an exception. Note: Persons in Class-A dwellings will normally not notice vibration	0.1
Class B	Corresponds to relatively good vibration conditions. Note: Persons in Class-B dwellings can be expected to disturbed by vibrations to some extent	0.15
Class C	Corresponds to recommended limit value for vibrations in new residential buildings and in connection with planning and building new transport infrastructure Note: About 15% of the affected persons in Class-C dwellings can be expected to be disturbed by vibrations	0.3
Class D	Corresponds to vibration conditions that ought to be achieved in existing residential buildings. Note: About 25% of persons can be expected to be disturbed by vibration in Class-D dwellings. An attempt should be made to meet Class-C, but Class-D can be used when the cost-benefit considerations make it unreasonable to require Class-C	0.6

These limit values are rated as vibration velocity which is frequency weighted according to ISO 8041 (Figure 5-2). To constitute a statistical dose measure of the exposure they refer to the 95-percentile taken over the 1s maximum value from at least 15 typical vibration events.

The criterion values in NS 8176 are based on dose-effect curves as shown in Figure 5-4. The curves are established through a sociological investigation with about 1500 respondents. Ref. Turunen-Rise et al. (2003). The investigation did not reveal any consistent effect of number of vibration events per day given the range of variation covered in the study.



Key

1 Perceives vibrations
2 Highly, moderately and slightly annoyed of vibrations
3 Highly and moderately annoyed of vibrations
4 Highly annoyed of vibrations

Figure 5-4 Doze- effect curves for peoples reaction to vibration in their homes caused by near by land based transportation. Based on Norwegian sociological study with 1500 respondents. From. NS 8176.

There are clear similarities between building vibration caused by road and rail traffic and vibration induced by sound pressure from low frequency military sources. However, there are also important differences, particularly with respect to duration of events and number of events per day, week or year.

Even though NS 8176 does not deal with airborne sound, the standard is relevant in that respect as there is a fuzzy borderline between detectable airborne sounds and vibrations at such low frequencies.

5.4 Empty spots

Many military LFN sources are typically ”single event” sources: detonations, heavy weapon, etc. Most of the existing knowledge and current regulations, however, seem to be related to stationary, steady state sources: windmills, ventilation systems, industry, etc. An obvious task is therefore to expand the search in existing literature data bases and other sources to find out to what extent existing dose-response functions and noise regulations are applicable to single event sources of relatively short duration. The impact of short LFN events is also likely to be dependent on repetition rates, duration of quiet intervals, and time-of-day. This search must include both occupational and environmental aspects.

The criteria curves for LFN annoyance used in several European countries more or less coincide with the normal hearing threshold. The hearing threshold is constant for signal durations above “some milliseconds”, but the threshold increases for very short signal durations.

Several studies report changes in the dose-response functions when LFN is present in various situations. Ordinary audible sounds/noises at moderate levels seem to reduce the annoyance caused by LFN. In other words: LFN in an otherwise completely quiet surrounding is more annoying than if other sounds (at higher frequencies) are present. Such information is important for assessment of LFN in quiet (remote) areas.

Another situation is assessment of LFN from outdoor sources in a building with improved sound insulation. Normal building acoustic improvements are usually not very effective at low frequencies. Such abatement measures may therefore reduce the audible sounds (high and middle frequencies), and thus make the LFN more prominent and therefore more annoying.

There are studies that indicate that noise from transportation sources in combination with ground/floor vibrations is assessed to be more annoying than the same noise without vibrations. Similarly, ground/floor vibrations are assessed differently depending on whether or not a corresponding audible sound signal and rattling is present. We do not have reliable information on how combinations of LFN and vibrations are assessed compared to airborne LFN alone. This issue must be further addressed.

In summary; there is a lack of knowledge on the combined effect of LFN, whole body vibration, rattling, and ordinary audible sound. Particularly the border-line between sensing of infrasound versus whole body vibration at very low frequencies need to be investigated. Further there is a lack of knowledge on the applicability of the existing regulation values for LFN and whole body vibration for typical short duration, infrequent military events.

6 Measurement techniques

6.1 LFN - Problems and challenges

Most current international standards for building acoustic measurements are limited to frequencies above 50 Hz. (Lowest relevant frequency band is 1/3 octave centred around 50 Hz). The most recent standard, ISO 16032, for measurement of noise from "service equipment" in buildings also include the octave band centred around 31.5 Hz, and uses C-weighting for the result.

Even at these frequencies the measurement of indoor sound pressure levels are quite challenging. It is necessary to use extensive averaging techniques in order to get representative results that can be reproduced with sufficient accuracy. Further it is essential that the noise in a room is quantified in a way that really reflects how it will be subjectively perceived.

At low frequencies the wavelength will approach and supersede the dimensions of the room. The sound field is therefore no longer diffuse, and modal shapes and spatial non-uniformity become an issue. The description of the sound pressure level of a non-diffuse sound field using a single number, can be meaningless.

Figure 6-1 shows the transfer function between a single source and a microphone located in a room. The solid black line is the result of a sine sweep and the red line is the 1/3 octave response. The green line is the theoretical diffuse response. For this particular room the actual transfer function for frequencies below a few hundred hertz will deviate considerably from the theoretical diffuse field.

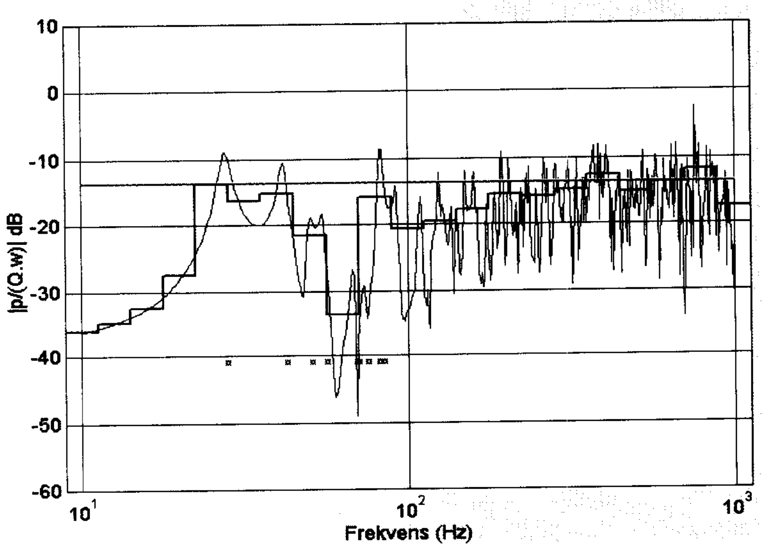


Figure 6-1 The transfer function between a single source and a receiver in a room

Sine waves are often replaced by narrow band noise signals for building acoustic measurements in order to avoid special room resonances. Figure 6-2 shows the relative sound pressure level in a room 6.2 x 4.1 x 2.5 m. The point source is located in a corner, and the sound pressure level is calculated at different distances from the source.

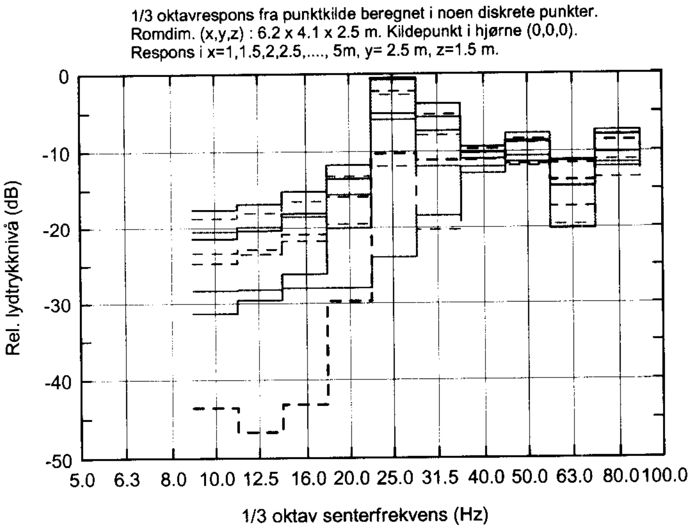


Figure 6-2 1/3 octave response from a point source located at xyz (0,0,0). Room dimensions: 6.2 x 4.1 x 2.5 m. The relative sound pressure level is calculated for positions x = 1.0, 1.5,...5.0 m , y = 2.5 m and z = 1.5 m. At 10 Hz the relative difference is about 25 dB

The results of practical measurements of the sound pressure level in a room of 102 m^3 are shown in Figure 6-3. The measurements were carried out according to international standards. At 50 Hz the standard deviation is 5 dB and it is increasing towards lower frequencies. It may thus be difficult to document improvements of the sound insulation at low frequencies.

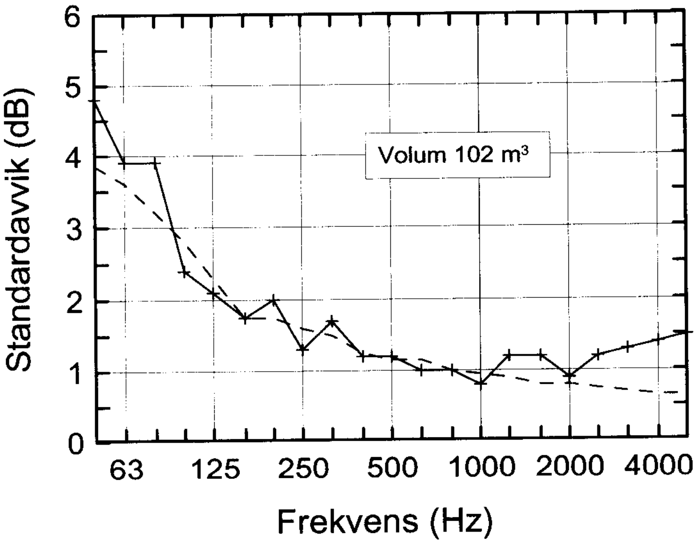


Figure 6-3 Measurement of the sound pressure level in a room of 102 m^3 according to international standards. At 50 Hz the standard deviation is about 5 dB.

The examples in figures Figure ***6-1*** - Figure ***6-3*** clearly illustrates the difficulties in performing accurate building acoustic measurements at low frequencies.

The transmission and reflection properties of a construction will vary depending on the direction of the incident sound wave. The sound insulation for LFN will therefore depend on the location of the noise source relative to the building. This effect is especially prominent for double walls and similar complex constructions.

6.2 Building vibration

The basic principles for measurement of vibration with respect to its effect on people are defined in the international standard ISO 8041. For people in buildings the dominant vibration effect is whole body vibration, which covers the frequency range from 1 to 80 Hz. Details on how to measure and evaluate whole body vibration are defined in ISO 2631. Part 1 of this standard deals with vibrations which may effect health and working efficiency, while Part 2 deals specifically with vibrations in buildings and the effect on peoples' comfort. None of the above standards do, however, specify at which location in the building to do the measurements, and how to treat repeated and transient vibration. Neither do they give acceptance criterion values for vibration annoyance in buildings.

To evaluate a recorded vibration signal with respect to human response, the signal needs to be filtered by the sensitivity curve used as a weighting function, as defined in ISO 8041. To ensure that signal components outside the 1-80 Hz frequency range do not contribute to the rating, a band limiting filter is specified. Figure 6-4 shows the function.

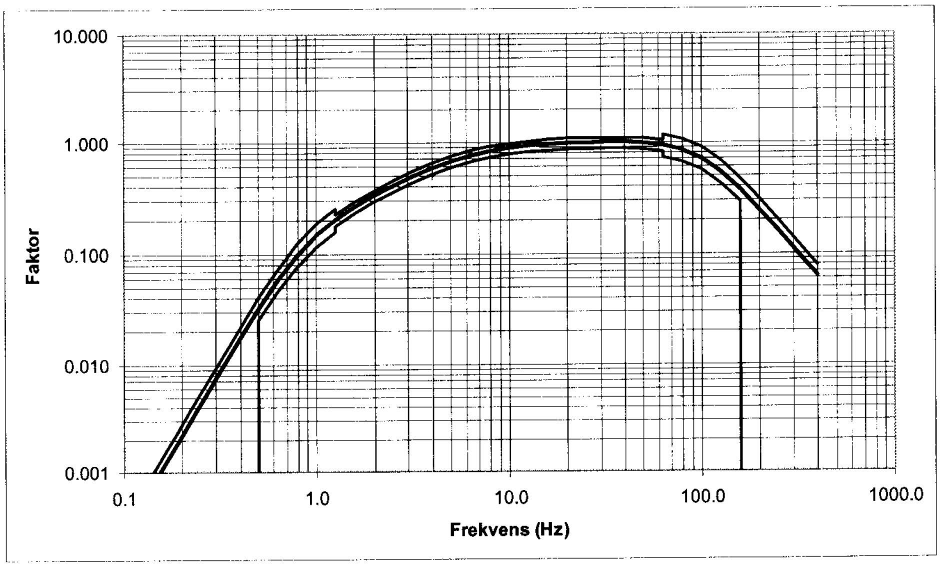


Figure 6-4 Frequency weighting function for human exposure to whole body vibration according to NS 8176, including band limiting filter and instrument tolerance. Frequency range for whole-body-vibration; 1-80Hz is highlighted. The weighting function is identical to the one defined in ISO 8041, but converted from acceleration to velocity.

6.2.1 The Norwegian standard NS 8176

The main standard used in Norway for measuring building vibrations with respect to their effect on people is NS 8176 . This standard is primarily intended for land based transportation, but the measurement procedure of NS 8176 is considered relevant also for the assessment of vibration from low frequency military sources, and the effect of these vibrations on humans. A weighting function as presented in Figure 6-4 is applied to the data within this frequency range to better reflect the effect of the vibrations on the human body. Only the floor vibration is measured, in either the bedroom or living room, in the position and direction where the highest values of weighted vibration occur. This is usually in the middle of the largest floor span. The largest one second RMS value of the weighted signal during the event should be taken as the vibration exposure of a single vibration event.

Both the maximum weighted vibration and the statistical weighted maximum are calculated to assess the vibration measure; the "statistical maximum". It is defined as the vibration value which is not exceeded by 95 % of events. The standard requires at least 15 events for each measurement position, to obtain a sufficiently reliable estimate of the 95%-value.

6.2.2 Improvements to current measurement techniques

In the LF region the interaction between vibration of building elements and the exterior and interior noise is important. This produces a demand for measuring the vibration of the walls, roofs and ceilings in addition to the floor. Simultaneous measurement of both sound pressure and vibration is necessary to capture the interaction. In order to capture also the higher modes of vibration in these elements either several sensors are required on each or the position of a single sensor must be carefully chosen. Only the vibration normal to the element surface is required.

When measuring the vibration of building elements care must be taken not to affect the element by the measurement sensor. For example, measuring window pane vibrations with a normal accelerometer will produce erroneous results as the natural frequency of the pane will be reduced by the accelerometer mass. The use of lightweight and possibly cordless sensors may be appropriate here.

In order to produce a good statistical maximum value many events are required. In the case of airborne sources the variability in the position and strength of events is especially large, producing correspondingly variable measurement results. For verification of insulation improvements, where measurements are separated in time, it is suggested that a standardized low frequency sound source be used, so that many controlled events can be recorded.

6.3 Necessary research

There is an urgent need to develop new methods for building acoustic measurements at low frequencies, $f < 50$ Hz. The challenge is two-fold. The methods must yield “sufficiently accurate” results in the sense that the results can be readily reproduced by repeated measurements. It is also vital that the “results”, i.e. the parameters that are being measured, are relevant for the intended purpose. Measurement of LFN insulation, for instance, must really reflect the way the insulating properties are subjectively perceived. Methods to efficiently process multi channel simultaneously measured sound and vibration data to capture the mutual interaction is needed. Measurement methods that can quantify rattling in a representative way and how it relates to the LFN and building vibration are also in urgent need.

7 Low Frequency Sound and Vibration Insulation

7.1 General considerations

LFN can enter a building through various paths. Regular airborne sound can propagate into a building by exciting walls and other building elements and by air pressure "leaking" through openings / non-air tight elements. The sound waves outdoors can also excite the entire building, make it vibrate, and cause secondary noise emission and rattling inside. It is therefore necessary to regard sound insulation and vibration insulation as a complex quantity, and the two phenomena can not be dealt with separately.

Full scale measurements on real buildings have shown that vibration from military low frequency sources are generated by the sound pressure acting on the building and the ground in the vicinity of the building; Path A and Path B in Figure 7-1. Which path dominates depends on the building structure and ground condition. Vibration transfer as seismic waves through the ground all the way from the source; Path C, will usually not contribute, since seismic waves attenuate much faster than sound pressure waves. The only exception is well buried or underground explosions.

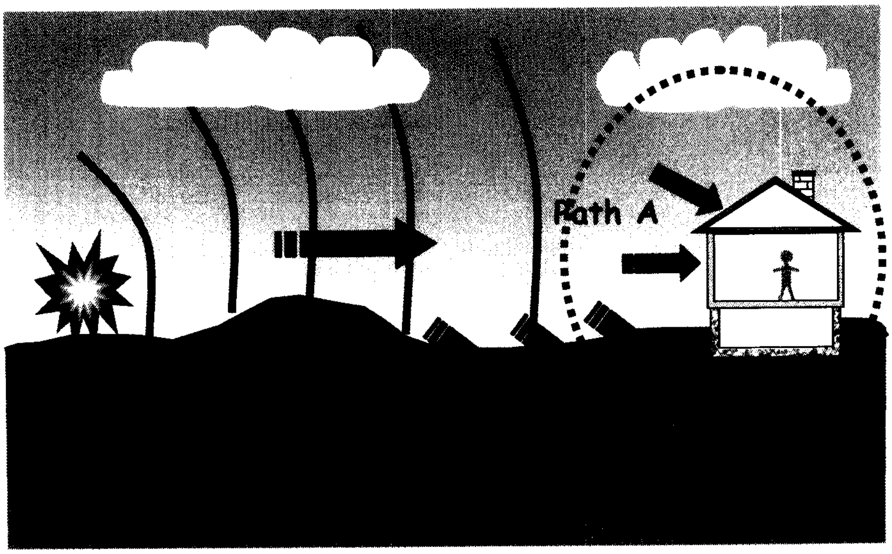


Figure 7-1 Propagation paths from LF military source to building vibration. Path A: Sound pressure action directly on building or building elements. Path B: Sound pressure acting on the ground around building, causing local ground vibration transferred into building. Path C: Ground vibration at source transferred as seismic waves to building.

Most international standards for building acoustic measurements are limited downwards to the 1/3-octave around 50 Hz. Different national LFN regulations, however, specify limits down to 10 Hz and below. The lower 2-3 octaves are therefore not covered by standards, neither for measurements nor for recommended requirements.

Practical experiments indicate that the sound/vibration isolation at very low frequencies is governed by a number of resonances, not only defined by single building elements, but also by the whole building structure itself.

Typical room dimensions corresponds to sound frequencies in the range 70-150 Hz. Double wall constructions have resonances typically in the range 60 – 200 Hz.

Structural resonances in floors and walls occur mainly in the frequency range 10 – 50 Hz (fundamental), and the first eigenfrequencies of a whole building are normally in the range 0.5 - 10 Hz. This coincides with the dominant frequency range of sound pressure from typical LF military sources.

Practical experiments indicate that for frequencies below about 10 Hz the resonances are defined by "whole building" vibrations. Such resonances are extremely difficult to manage in a retrofit situation, as the dimensions and geometry of the building itself are important parameters.

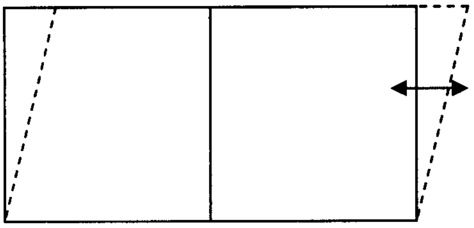


Figure 7-2 At very low frequencies, f < 10 Hz, the whole building can be excited as one object

Resonances in the intermediate range 10 – 100 Hz are mainly defined by the interaction between large building structures (walls, floors, etc.) and the coupling between them. These resonances can therefore more readily be dealt with in respect of response mitigation / insulation.

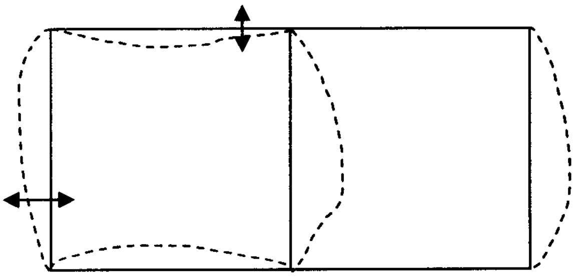


Figure 7-3 At frequencies 10 Hz<f<100 Hz the resonances are given by interaction between room and building elements

Above 100 Hz the resonances are chiefly defined by parameters within the separate building elements themselves.

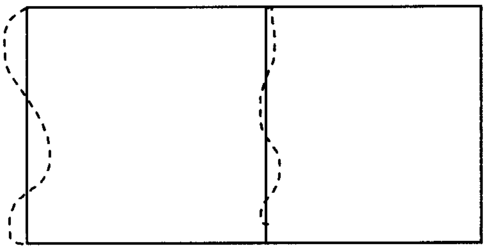


Figure 7-4 For frequencies f >100 Hz the resonances are given by the properties of the single building elements

A conventional way of achieving good sound insulation is to "control" the resonances by varying mass and stiffness so that the resonances are located "well outside" the relevant frequency range. This method is well documented and experience from both field and laboratory experiments has shown that good sound insulation can be readily achieved for frequencies 100 Hz and up.

When the frequency range is expanded to include LFN, it may no longer be feasible to locate the resonances "outside the relevant range". First of all it may prove impossible to achieve sufficiently low resonances, and secondly the whole building structure may be excited. The actual dimensions and building geometry will therefore be important parameters for the LFN and vibration insulation.

When building resonances occur within the relevant frequency range, it will be necessary to focus on damping mechanisms (loss of energy) in order to reduce the effect of these resonances. Important parameters are thus not only dimensions and the material of the building elements themselves, but also the way these elements are joined together. This includes both joints between single elements, e.g. between walls and floors, and intra-element junctions such as double walls, loosely coupled panels, etc. In general, braking symmetries and including variability in stiffness and span among structural elements in a building will tend to "soften" resonances and make the building less vulnerable to LFN.

In some special cases it may still be possible to achieve good LFN insulation by "controlling" the resonances. If the LFN sources is unique and the frequency spectrum is well known, it may be possible to vary mass and stiffness of the construction so that the building resonances are not excited. The insulation for noise from a definite source can therefore be quite good, even if the "general LFN insulation" is rather poor.

At the very low end of the frequency range, below 10 Hz, active damping of resonances may prove to be an effective solution. Increasing the stiffness and maintaining the internal damping, which is not easy, may also be a possibility for insulating LFN in compliant structures.

7.2 Present knowledge

Techniques for achieving good sound insulation are well known for frequencies above 100 Hz. Theoretical models that can be used to calculate the sound insulation at these frequencies also exist.

There are some data and results from practical experiments for sound insulation in the frequency range 50 – 100 Hz, but below 50 Hz very little systematic knowledge is available.

7.3 Empty spots

Models for calculation of the insulating properties of building constructions at low frequencies, below say 50 Hz, are also almost non-existing.

Nordic building traditions call for light constructions. There is thus a great demand to find constructions that have sufficient mass or stiffness to control the resonances at low frequencies. Dynamic response properties of typical Norwegian single- or multiple family buildings are generally not well known, and particularly not how these properties develop over the life-time of the building.

LFN insulation also calls for constructions with internal damping. Damping mechanisms in complex structures at low frequencies are not well known. This is especially true for "loosely coupled" elements, sandwich (stacked) panels with little or no internal coupling (adhesives, screws, nails, etc), double wall constructions, etc.

The interaction between LFN and structural vibration in typical homes is not properly understood. One does for instance not know whether a specific coupled acoustic-structural resonance in a room is actually driven by the structural elements radiating the sound, or vise-versa; the sound that has entered the room in another way drives the vibration of the structural elements, and how does that change when e.g. a window is opened. This illustrates the urgent need to understand such essential mechanisms.

Figure 7-5 illustrates this issue as an example: A floor is assumed to vibrate just at the threshold of whole body perception (0.15mm/s). What is plotted is the (linear) sound pressure just above the floor for the two situations: (A) – Red curve: The floor vibrates and radiates the sound into the room, i.e. the sound is "structure driven". (B) – Black curve: The sound pressure in the room excites the floor vibration. The pressure is just high enough to make the floor be at the perception threshold at each frequency, i.e. the vibration is "acoustically driven". The same figure also plots the hearing threshold according to ISO 226 and the various national LFN regulations from Figure 5-1. What can be seen from the figure is that for the "structure driven" case, the perception should be expected to be dominated by vibration for frequencies below about 20Hz and by LFN for higher frequency. For the "acoustically driven" case the perception will be dominated by sound / infrasound all way down to about 10 Hz, there vibration is expected to take over to dominate the perception. The figure must be taken as indicative only, since the sound radiation model is very primitive.

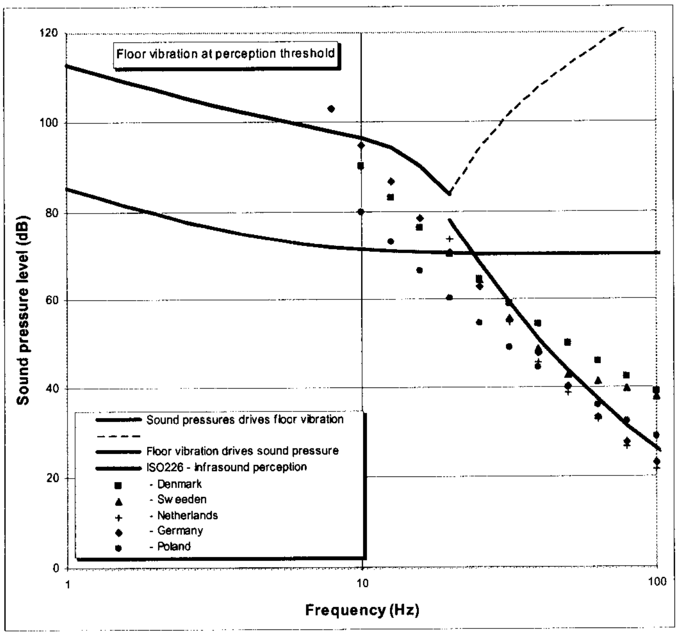


Figure 7-5 Indications on border-line between sound pressure- and vibration perception at low frequency.

8 Conclusions

There are a number of unresolved issues concerning LFN and vibration insulation in buildings. In each of the previous chapters necessary research items have been identified.

Existing standards and regulations regarding LFN impact seem to concentrate on stationary steady state noise sources, such as heavy machinery, ventilation systems, wind mills, etc. Most military LFN sources are impulsive, and it is not clear whether exciting standards are applicable to this type of noise. Standards and regulations for building vibration can to some extent be applied for vibration excited by LFN from military sources. Combinations of sound and vibrations can also give other reactions than separate exposure to these stimuli. Rattling may add to the adverse reaction.

Most standards for indoor sound measurements require that the sound field is diffuse. At low frequencies this is no longer the normal situation, and the sound field is highly dependent on the different room modes. Slight changes in the microphone position can give very different sound pressure readings. It is necessary to develop new measurement standards that will yield results that can be readily reproduced with sufficient accuracy. It is also necessary to determine how these measurements can be related to subjective parameters.

Similar considerations apply to LF vibration measurements. The magnitude of the vibration is highly dependent on the measurement position, and the vibration may be modified by the sensor (vibration pick-up) itself. The relationship between vibration levels and subjective response is also unclear. Sound pressure and structural vibrations interact at low frequencies. Simultaneous measurement of noise and vibration is therefore required.

Conventional sound insulation techniques typically focus on single building elements such as windows, facades, etc. At very low frequencies the coupling and interaction between these elements become important for the total sound insulation. These mechanisms are not readily controllable, and models for calculation of LFN and vibration insulation are therefore not available. A compilation of “good practice examples” could be a start.

It is also necessary to develop new constructions with high internal damping at low frequencies.

9 Recommendations for further work

In order to learn more about LFN and vibration insulation in buildings and related issues, the following concrete work packages are being proposed:

- **relevance of existing assessment criteria / recommended criteria for military sources**
  The different national standards for LFN assessment are primarily valid for steady state signals. The criteria curves are quite similar to the normal hearing threshold. This threshold generally shifts upwards for signals of short duration. Relevant signal durations can be derived from sound from artillery and detonations.

  Simple threshold experiments can be carried out comparing the response to signals of long and short durations. Similar studies can be performed to check the "masking" effect of noise at higher frequencies. Additional experiments should be made to assess the combined effect of LFN, vibration and rattling.

  Existing standard likes NS8176, ISO 8041 and DIN 4150 for assessing whole body vibration in buildings have mostly been developed for transportation noise/vibration sources. Simple comparison studies can reveal if these criteria curves also hold for impulsive excitation sources.

  Records of relevant complaints on LFN and vibration should be systemized and analyzed statistically. Sociological studies may be added to supplement the database.

- **measurement methods**
  It is vital to develop new measurement methods that can be used for low frequency characterization of sound and vibration properties. The methods must not only be repeatable, but it must be shown that the measurement results are relevant for the LFN parameters that contribute to the annoyance.

- **building response to impulsive sounds**
  In the pilot study results form scale model experiments were demonstrated. These experiments showed how the response shifted from single element resonances to "whole building" resonance at very low frequencies. The response was measured using a continuous sine wave excitation signal.

  These experiments can be repeated by substituting the continuous excitation signal with an impulsive signal. The results will show if models for building vibrations can be generalized to also include impulsive sources.

  The model experiments should also be used to show if reciprocate measurement technique (measuring from inside and out instead of from outside and in) applies for impulsive signals.

- **best practice**
  A systematic survey and documentation of existing building constructions that are known to have good LFN and vibration insulation properties should be carried out. It has been known that presumably similar constructions may have very different insulation. This may be explained by small differences in construction details. Such differences should possibly be documented. The documentation must include both sound and vibrations properties.

Measure and build a database on dynamic properties, particularly natural frequency and damping of various typical Norwegian inhabited dwellings. Study effect of structural solutions, inventory and age.

- **understand LFN and structural vibration interaction / simulation model for insulation**
  Analyze existing outdoor and indoor sound and vibration data measured in two buildings at Rødsmoen 2005, to obtain fundamental understanding of how sound and vibration interact. Data from Gildeskålveien and from the model experiments may also be further analyzed in this respect.

  Use this understanding together with dynamic properties from the "best practice" to develop numerical simulation models (FEM, DEM). "Calibrate" the model against the measurements. Use the model as a "numerical laboratory" to test out various approaches for LFN and vibration insulation of buildings.

  Validate the model against results from "experimental design".

- **experimental design**
  Experimental full scale building elements, building parts or "idealized building" should be tested with respect to LFN and vibration response and insulation under controlled laboratory conditions, in order to derive at practical solutions that can be used in the field. Both sound and vibration insulation properties must be investigated.

- **participation in international studies**
  In Norway little work has been done in the LFN area. Internationally there are several ongoing studies, and these works are periodically reported at a special series of annual conferences, "International Conference on Low Frequency Noise and Vibration and its Control". Norwegian participation in these conferences, and similar ones, should be made possible through a LFN research program. Establish international co-operation to get access to research results through active involvement, and get international partners/ sponsors for research and development activity in Norway.

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Appendix

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