Proceedings of the 9th International Meeting on Low Frequency Noise and Vibration, May 17-19, 2000, Aalborg, Denmark

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Publication date:
2000

Citation for published version (APA):
Møller, H., & Lydolf, M. (2000). *Proceedings of the 9th International Meeting on Low Frequency Noise and Vibration, May 17-19, 2000, Aalborg, Denmark*. Aalborg Universitetsforlag.

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Logo and cover design: Morten Lydolf

Printers: Centertryk

ISBN No. 87-90834-06-2

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Preface

It is now 20 years since the first open, international conference on low frequency noise and vibrations was held in Aalborg - namely on 7th-8th May 1980.

Since then much development has taken place and we have learned a lot. Some things have been clarified, whereas others require a continued effort.

The subject has been allocated its own international journal *Journal of Low Frequency Noise, Vibration and Active Control* published by Multi-Science, and a number of conferences have been held on this subject with participants from all over the world. If we include an invited meeting in Paris in 1973 it turns out this meeting will be number 9 in the series.

We are especially pleased to welcome the Meeting back to Aalborg.

We have received a total of 28 interesting contributions and we are looking forward to a successful meeting.

The Organizing Committee

Henrik Møller Morten Lydolf Lone Engen

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Noisy machines in buildings

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Introduction

A good acoustical environment both inside and outside houses are more and more appreciated by users and residents. There is a need for a quality declaration to be made for buildings, flats and nonresidential premise so that acoustic qualities may be clear to all. Such quality classification is also recommended in the State Commission on Enquiry ”Action plan against noise”.

In older days artisans had their shops with rather noisy production gathered in industry houses. Nowadays there are instead more commen to have print shops and other noisy activities in houses near to flats or offices as neighbours who are really disturbed in there work by vibration and noise.

Noise criteria

In Sweden noise critera are given in for exemple the ”Acoustic Guide” distributed by the Swedish Council for Building Research. The Acoustic Guide is a classification system for acoustic quality within buildings based on the standard classes. The classification system is coordinated with the Action plan against noise and with the Building Regulations of the Swedish Board of Housing, Building and Planning.

By selecting a standard class and satisfying all the reguirements in this class, the building or premises can be acoustically classified in the desired quality level.

There are proposals given to highest total acceptable noise levels dB(A) from services and appliances , technical installation that causes noise with long duration within a house property. In the tables 1 and 2 proposed highest levels dB(A) in offices and departments are shown

Table 1. Noise from services and appliances in residential buildings.

Space	Maximum total sound level dB(A) due to services and appliances
Acoustic class A	
Bedroom	20
Living room	25
Kitchen	30
WC, bathroom, etc	35
Acoustic class B	
Bedroom	25
Living room	30
Kitchen	35
WC, bathroom, etc	40
Acoustic class C	
Bedroom	30
Living room	30
Kitchen	35
WC, bathroom, etc	40
Acoustic class D	
Bedroom	30
Living room	35
Kitchen	40
WC, bathroom, etc	45

Table2. Noise from services and appliances in office buildings.

Space	Maximum total sound level dB(A) due to services and appliances
Acoustic classes A and B	
Office rooms, smal conference rooms, discussionn rooms, rest rooms, terminal rooms, reception and despatch areas	35
Staff rooms, landscaped offices, shops etc	40
Cirridors, entrances, WC, showers, changing rooms, data rooms etc	45
Parking decks, goods recption areas, store rooms, wind screens at entrance etc	55

For noise of shorter duration, the acceptable total maximum sound level is 5 dB(A) higher.

Even if those proposals of maximum acceptable levels are fullfilled, people many times are still annoyed by the noise.

The Swedish Society for Health and Welfare has therfore prepared a proposal, SOSFS 1996:7, for low frequency noise levels in 1/3-octave bands. The guidelines are shown in table 3.

Table 3. Recommendations för estimate of sanitary inconvenience caused by equivalent low frequency noise inside houses.

1/3 octave band Hz	31.5	40	50	63	80	100	125	160	200
Equivalent SPL dB	56	49	43	41.5	40	38	36	34	32

Vibration criteria

In the Swedish Standard "Measurement and guidelines for the evaluation of comfort in buildings" , SS 460 48 61 following weighted vibration velocity values in the frequency range 1 – 80 Hz are given for determining comfort in buildings, see table 4. The standard is based upon the International Standard ISO 2631-2. The weighting curves are shown in figure 1.

Table 4. Guidelines for vibrations in buildings in accordance with SS 460 48 61.

Amount of disturbances	Vibration velocity mm/s
Very little	0,4 – 1,0
Probable	> 1,0

The values are designed for the maximum of measured RMS value.

The threshold of sensitivity for vibration velocity in buildings is quite near to 0,1 mm/s.

Some examples of different types of disturbances

Print shops

Complains about annoying noise from a print shop had for a very long time been presented by a owner to a flat. The printshop was located on the same level in the neighburhood in a nearby building. The noise source was a four colour offsetpress with it´s complementing equipment. The measured noise level within the bedroom in the flat at normal printing speed, 10 000 ex/hour, was from the beginning about 35 dB(A). The dominating 1/3-octave band level for the dB(A) level was 125 Hz but even levels at 40 and 80 Hz had to be decreased. In accordance to the proposal from the Swedish Society for Helth and Welfare the low frequency noise levels were too high.

From the measurements we could certify that the problem was the transmission of structure borne noise. The higher frequency part of the noise, 315 Hz was generated by the main motor boltmounted to the shopfloor without any vibration isolation. The offsetpress itself had a vibration isolation with too high mounting frequnecy, about 60 Hz.
After vibration isolation of the main motor correctly with a rather weak isolation the noise level was decreased to 30 – 32 dB(A). In the next step with weaker vibration isolation of the four print devices the noise level was decreased to 28 dB(A) and the low frequency noise levels proposed by the Swedish Society for Health and Welfare were met.

In another case where people in an office made complains at a four colours offsetpress installed in a shop without any vibration isolation we made comparison vibration measurements on an equal offsetpress that should have been installed with vibration isolation. The measurements were made in the vertical direction in totally 8 measuring positions on the concrete floor along with the press. The both concrete floors should have about the same thickness and the building construction should be quite equal.

The results in 1/3-octave bands indicated no significant differences in vibration velocity levels for the two presses. When we measured the vibration velocity levels we could see with our eyes the isolation of the two first print units so we were convinced that even the other two print units had the same vibration isolation.

The conclusion was that all of the print units were not vibration isolated. The level of the floor was not exactly the same over the area of the press installation. In the other end of the press the floor level was too high so they did not manage to install those units with any vibration isolation.

Case 1
In a dwelling where the family had moved down in the house to a bigger flat they made complains at an annoying noise in their bedroom normally coming one or two times at the end of the day or in the beginning of the night. But it could also come early in the morning.

We installed a sound level meter and a accelerometer with a charge amplifier connected to a DAT-recorder and the family had to start the DAT-recorder when they found the noise annoying. They made recording during five days.

The analysed results of the recordings showed a pure tone in narrow band with a constant frequency of 49,06 Hz, resolution 0,31 Hz. This tone caused a noise level of 30 – 32 dB(A) in the bedroom. The duration of the tone could be in the range of 1 – 2 minutes. We have looked through all the house in order to try to find the source and been in contact with the subwaypersonal and others in the nearfield of the house but we have not found the source.

Case 2

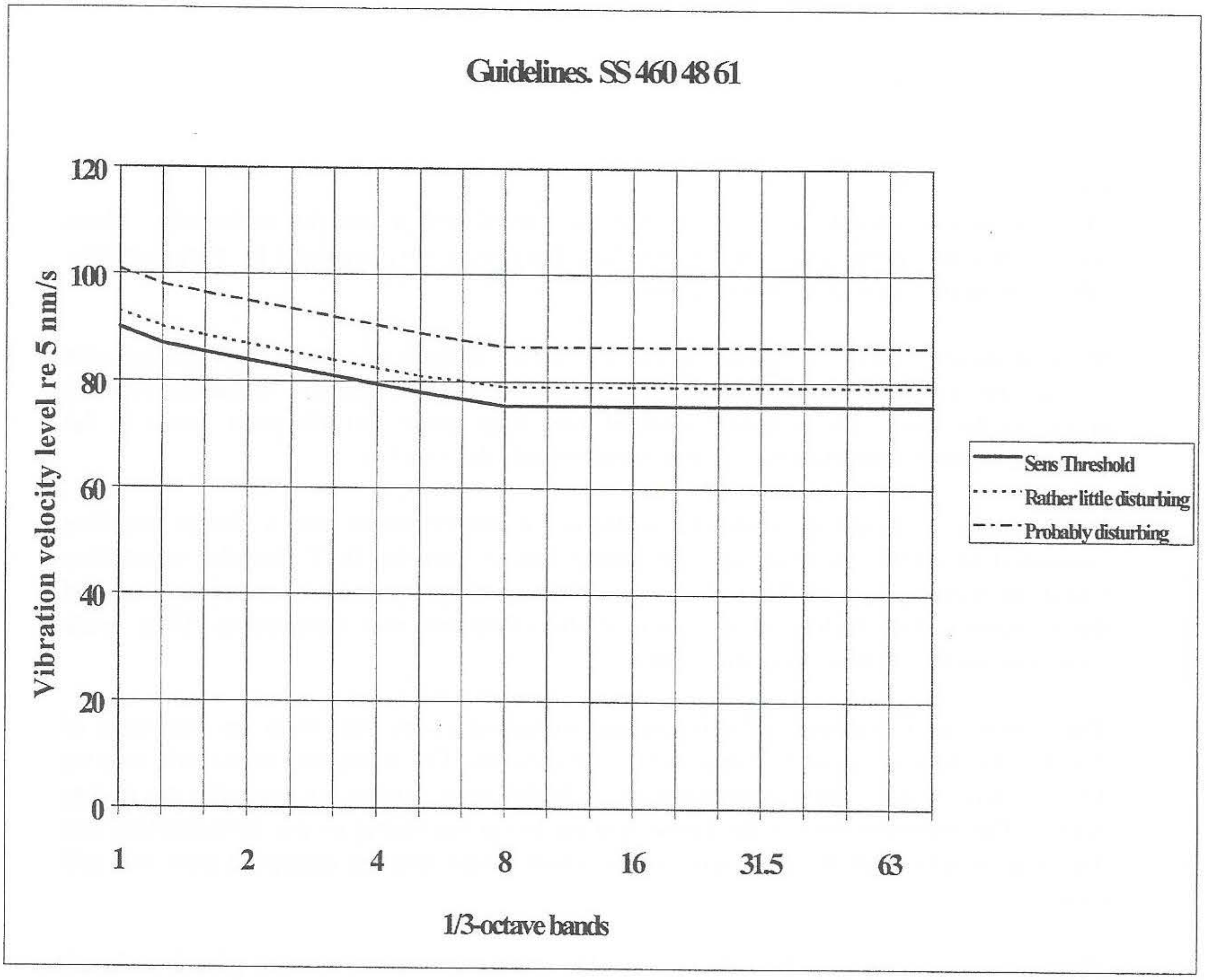
The attic in a five levels living house had been build with a new flat in the attic. There was a problem for the family in the new flat. They were very annoyed by very sensitive vibrations in the floor of their living room.

We first started to put a longtime measuring device in the living room, measuring noise outside the window, inside in the living room and also the vertical vibration velocity levels on the floor. These results showed very high noise and vibration levels in the livingroom but no correlation with the noise outside the window.

Next step was to install a sound level meter and a accelerometer with a charge amplifier connected to a DAT-recorder and the family had to start the DAT-recorder when they found the noise annoying. When I installed the recording equipment I could myself feel the vibrations. The feeling of direction of the vibrations was indefinable. They made recording during a rather long time, ten days.

The narrow band analyses of the recordings indicated a pure tone with the frequency of 8,9 Hz. The duration is in the range of 60 – 90 secunds. The disturbing tone could start up 15 to 20 times a day with a vibration velocity higher than 1 mm/s but normally not during nights. The representative of the house told me in the beginning av our investigation that they had switched off the electricity in the whole house and the annoying tone was still there.

We have not been able to find the source. The recommendation we will give is to break the woodenfloor and make it much stiffer.



Figur 1. SS 460 48 61, guide lines

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Low Frequency Noise "Pollution" Interferes with Performance

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Summary

In the study, 32 subjects performed four performance tests when exposed to a mid-frequency noise or a low frequency noise, both at a level of 40 dBA. The results indicated that low frequency noise interfered with a proof reading test by decreasing the number of markings made per line read. The results furthered showed that the response time in a verbal grammatical reasoning test was longer over time in the low frequency noise exposure. Subjects sensitive to low frequency noise generally performed less well and also reported the highest annoyance due to low frequency noise. Noise at levels normally occurring in office-like environments, dominanted by low frequencies, may influence work performance and perception of annoyance and subjects classified as sensitive to low frequency noise may be at highest risk.

1. Background

The introduction of modern technology and computerised machinery has decreased the previously high noise exposure situation but introduced other types of occupational noises of more moderate noise levels. In many cases, the noise is dominated by the frequency 20 to 200 Hz (low frequency noise) caused by noise from ventilation/air condition systems but also by the lower attenuation by the walls, floor and ceiling. Data shows that low frequency noise has effect characteristics of the low frequencies that are different from other environmental noises at comparable levels [Persson Waye 1995, Berglund et al 1994]. Symptoms reported in connection with annoyance due to low frequency noise and which could reduce a person's working capacity are fatigue, headache and irritation [Tokita 1980; Nagai et al. 1989; Persson Waye and Rylander 2000]. A pilot study [Persson Waye et al 1997] indicated that a low frequency ventilation noise at a level of 42 L_{Aeq} could increase the time taken to respond in a verbal grammatical reasoning test [Baddeley 1968] and influence the working capacity, compared to a ventilation noise not dominated by low frequencies. Previous studies of effects due to low frequency noise [Persson Waye et al 2000] show that persons sensitive to low frequency noise were not necessarily sensitive to noise in general as measured by general noise sensitivity scales. It is therefore important to classify subjects not only after sensitivity to noise in general, but also more specifically sensitive to low frequency noise.

The present study was undertaken to further elucidate the influence of low frequency noise on performance attempting to answer the following questions: 1. Can low frequency noise at a level normally present in control rooms and office areas influence performance and mood? 2. In which tasks does the low frequency noise affect performance? 3. How is the performance effect affected by exposure time? 4. What is the relation between self rated-noise sensitivity and noise effects? 5. What relation is there between self-rated sensitivity to noise in general and to low frequency noise? Do these possible two types of sensitivity relate differentially to the performance effects?

2. Material and methods

2.1 Noise exposure. The subjects performed a series of performance tests when exposed to two types of noises, both at a level of 40 dBA. The reference noise (ref. noise) was recorded from a ventilation installation and had a rather flat mid-frequency spectrum. In order to obtain a low frequency noise sound pressure levels in the frequency region of 31.5 to 125 Hz were increased using a digitalised sound processor system [Aladdin interactive work-bench, Nyvalla DSP Stockholm, Sweden]. Furthermore, a tone at 31.5 Hz was amplitude-modulated with an amplitude frequency of 2 Hz. Figure 1 shows the equivalent third octave band sound pressure levels for the two noises.

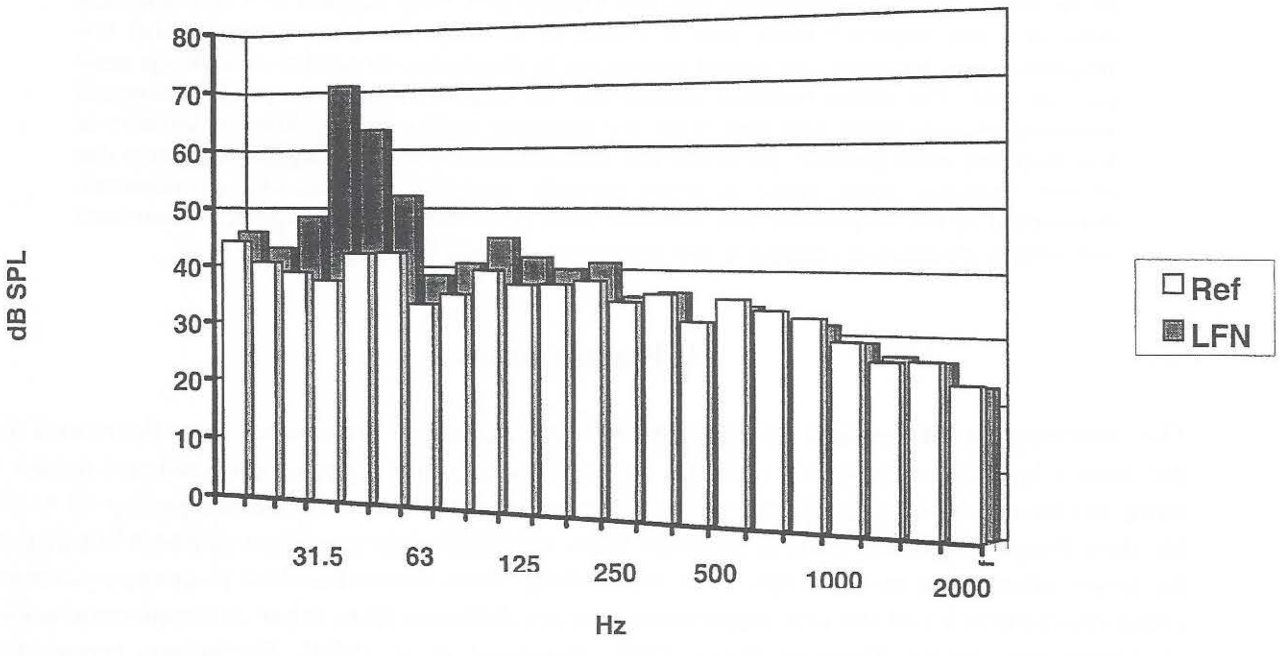

Figure 1. Third octave band sound pressure levels of reference and low frequency noise used during the performance tests.

2.2 Subjects and sensitivity. For the study 19 female and 13 male students, normal hearing and with an average age of 24.3, were recruited by advertising. The subjects were categorised as having a high or low sensitivity to low frequency noise (LFN) and high or low sensitivity to noise in general (NG), based on their scores on noise sensitivity questions. To assess sensitivity to LFN two questions "are you sensitive to low frequency noise" and "I am sensitive to rumbling noise from ventilation systems" were used. To assess sensitivity to noise in general the question "are you sensitive to noise in general" were used together with the total number of points scored in Weinstein's noise sensitivity evaluation questionnaire [Weinstein 1978].

2.3 Performance tests and questionnaires. In the experiment four performance tests were used. Test I was a simple reaction time test and test II a short-term memory test, performed together with a secondary test [Persson Waye et al 1997]. Test III was a proof reading test [Landström et al 1997] where the subject read a text on paper for ten minutes and marked errors in the text. Test IV was a computerised verbal grammatical reasoning test, translated into Swedish from the original version [Baddeley 1968].

Subjective reactions were evaluated using questionnaires. After tests II, III and IV, subjects rated how much effort they had used to perform each test. Before and after the test session a questionnaire evaluating moods [Sjöberg et al 1979] was completed. After the test session, the subject also filled out a questionnaire evaluating subjective work impairment, presence of symptoms experienced during or after the experiment and annoyance due to the noise present during the test. The subjects also received two questionnaires evaluating after-effects, to fill out one and three hours after the experiment had terminated.

To assess stress, saliva samples were taken and the amount of monoamineoxidase inhibitor and cortisol determined. Together with the saliva sample, the subjects also completed a stress questionnaire [Kjellberg et al 1989]. These latter data will be reported elsewhere.

2.4 test chamber. The experiment was performed in a 24 m^2 room, furnished as an office. The sound was emitted from four loudspeakers, hidden behind curtains and placed in each corner of the room. To amplify the low frequency noise, a subwoofer was used (ace-bass B2-50) which can reproduce frequencies down to 20 Hz. The background noise from the test chamber ventilation was less than 22 dBA, and the sound pressure levels for the frequencies below 160 Hz were below the threshold of normal hearing [ISO 398:1996].

2.5 Experimental design and procedure. The experiment had a 2 (noises) *2 (phases) * 2 (sensitivity groups) factorial design with repeated measurement in the first two factors and independent groups in the sensitivity factor. In the analyses of test I and IV a fourth factor, time blocks within the task, was added.

On a separate occasion the subjects learned the procedures and practised on short versions of the performance tests for about one hour with the ref. noise, at 35 dBA. Before each test, both written and verbal instructions were given and the importance to work as fast and correctly as possible was emphasised.

The main test consisted of two sessions, 2.5-3 hours each, on separate days and always in the afternoon. In the test session, the subjects were exposed either to the low frequency noise or the ref.noise. Half of the subjects started with the ref.noise and the other half with the low frequency noise. During each phase (A and B) in the test session, the subjects worked with the four performance tests. To minimise subjective influence due to the attitude to noise, motivation and own expectations before the test sessions, the written and verbal information about the experiment did not explicitly refer to noise exposure.

2.6 Analysis and statistical methods. Analyses of variance were performed to evaluate the influence of noise exposure, time, subjective sensitivity and their interactions on the different performance tests and subjective ratings. The p-values are based on degrees of freedom corrected with Greenhouse-Geisser epsilon when appropriate. The statistical analysis were carried out using SPSS [SPSS base 7.5 for Windows]. To evaluate the difference of means for specific periods, Student's t-test for dependent data was applied. When assumptions for ANOVA were not fulfilled, Wilcoxon´s sign-rank test for matched groups was used. Corrections of mass significance were done using Tukeys´ test for balanced data. All tests were two-sided and a p-value of <0.05 was considered as statistically significant.

3. Results

3.1 Performance tests. No difference between the noises were found for the *simple reaction time test*, the *short term memory test* or the *bulb test*.

In the *proof reading test*, no significant effect of the different noise exposures was found on *number of correct markings per line.* A significant two-way interaction between noise and phase, (F(1,31)= 10.069, p<0.005), was found for the *number of erroneous corrections per read lines.* From table 1 can be seen that the number of erroneous corrections was lower during phase B in LFN, but not during the ref.noise. A two-way interaction between noise and phase was also found for the *total markings* (correct and erroneous) per line, (F(1,31)=7.018, p<0.05).

		Reference noise		**Low freq. Noise**	
		Phase A	**Phase B**	**Phase A**	**Phase B**
Number of lines read	**All subjects**	**134**	**133**	**136**	**137**
	Sensitive LFN[3]	126	131	132	129
	Non-sensitive LFN[3]	144	136	141	148
	Sensitive NG[5]	128	135	139	134
	Non-sensitive NG[5]	139	132	133	140
Correct markings/line	**All subjects**	**0.55**	**0.52**	**0.55**	**0.49**
	Sensitive LFN	0.58	0.49	0.56	0.49
	Non-sensitive LFN	0.51	0.55	0.53	0.48
	Sensitive NG	0.54	0.51	0.53	0.44
	Non-sensitive NG	0.56	0.52	0.56	0.53
Erroneous corrections /line	**All subjects[1]**	**0.06**	**0.06**	**0.06**	**0.04**
	Sensitive LFN	0.05	0.05	0.06	0.04
	Non-sensitive LFN	0.06	0.07	0.06	0.04
	Sensitive NG	0.05	0.05	0.05	0.04
	Non-sensitive NG	0.06	0.07	0.06	0.05
Total markings/line	**All subjects[1,2]**	**0.13**	**0.13**	**0.13**	**0.10**
	Sensitive LFN[4]	0.13	0.12	0.13	0.10
	Non-sensitive LFN[4]	0.13	0.14	0.13	0.11
	Sensitive NG	0.12	0.12	0.12	0.11
	Non-sensitive NG	0.13	0.13	0.14	0.09

[1]: A significant two-way interaction between noise and phase.
[2]: A significant difference between the phases.
[3]: A significant three-way interaction between noise, phase and sensitivity to low frequency noise.
[4]: A tendency to two-way interaction between phase and sensitivity to low frequency noise.
[5]: A significant three-way interaction between noise, phase and sensitivity to noise in general.

Table 1. The results from the proof reading test for all subjects, subjects sensitive or non-sensitive to low frequency noise or noise in general.

Regardless of noise exposure, subjects sensitive to LFN made slightly fewer total markings than non-sensitive subjects. Subjects sensitive to LFN also read fewer lines, on average 129 compared to 142 for the non-sensitive subjects. There was a significant three-way interaction between noise, phase and LFN sensitivity (F(1,30)= 5.306, $p<0.05$). Subjects sensitive to LFN read a greater number of lines in phase B as compared to phase A during ref.noise and fewer number of lines in phase B compared to phase A during low frequency noise. The reverse conditions were seen for non-sensitive subjects.

The same analysis with subjects classified into general noise sensitivity showed partly different results. The difference between numbers of lines read between the groups was less pronounced (134 lines for sensitive subjects as compared to 136 among non-sensitive). The interaction between noise, phase and sensitivity was significant F(1,30)=7.976, $p<0.01$), but the pattern of a consistently lower number of lines read for the sensitive subjects was not found for phase A during low frequency noise.

A general tendency in the test, regardless of noise exposure or sensitivity, was the detection of fewer errors in phase B (F(1,31)=3.733, $p=0.063$), 61.5% as compared to 66.6% in phase A.

The results from the the *verbal grammatical reasoning test* demonstrates that no difference in total response time was found between noise exposures for phase A. The mean response time was shorter during phase B as compared to phase A in both noise conditions, (3704 versus 3924 ms, F(1,31)=9.014, $p<0.01$) but the decrease of response time in phase B was less pronounced during low frequency noise. The two-way interaction between noise and phase was significant (F(1,31)=5.750, $p<0.05$).

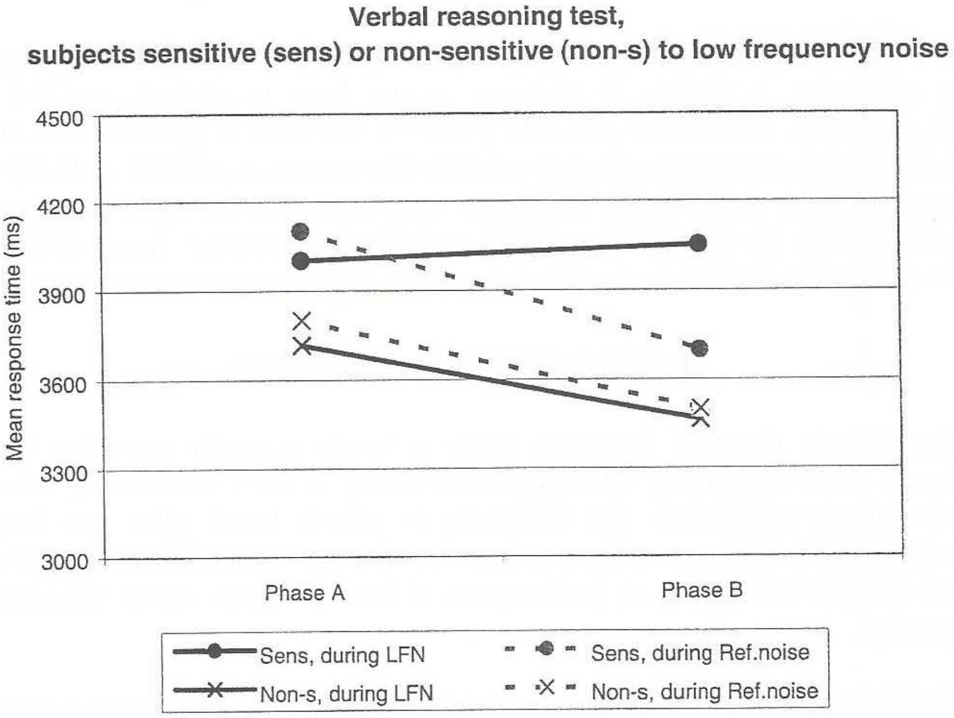

Figure 2. The average response times (ms) in the different parts of phase B of the verbal grammatical reasoning test during low frequency noise and reference noise related to low frequency noise sensitivity.

Subjects sensitive to LFN had on average a similar response time between noises in phase A. In Figure 2 can be seen that the difference in response time during low frequency noise and ref.noise was larger in phase B, and a tendency to a three-way interaction between LFN sensitivity, noise and phase was found (F(1,30)=3.319, p=0.078). For subjects classified as sensitive to NG, no difference between the noise conditions was detected.

3.2 Subjective estimations. The low frequency noise was rated as more *annoying* then the ref. noise (2.47 versus 2.00; F(1,31)=9.922, $p<0.005$). Furthermore, there was a two-way interaction between LFN sensitivity and noise (F(1,30)=6.534, $p<0.05$). Subjects sensitive to LFN were more annoyed by low frequency noise than by the ref. noise (3.1 compared to 2.3), while non-sensitive subjects reported on average the same annoyance after both noises (1.6). No significant difference between noises was found when the same analysis was done with subjects classified into sensitivity to NG.

Sensitive subjects, to LFN or NG, gave after both noises a higher rating of annoyance than non-sensitive subjects (2.7 versus 1.6; F(1,30)=14.911, $p<0.001$ and 2.7 versus 1.8; and F(1,30)=8.599, $p<0.01$).

LFN was considered to *impair the working capacity* more than the ref. noise (3.4 versus 2.6; F(1,31)=4.649, $p<0.05$). When the data was subdivided into the two noise sensitivity groups the noise difference was no longer present. Irrespective of noise, subjects sensitive to LFN or NG rated a larger impairment of the working capacity compared to non-sensitive subjects (3.6 versus 2.2; F(1,30)=5.554; $p<0.05$ and 3.7 versus 2.3; F(1,30)=4.411, $p<0.05$).

No significant differences between the noises were found on rated *effort.*

Annoyance due to low frequency noise was correlated to subjective estimation of the following symptoms, a feeling of pressure on the head (r_{xy}=0.664, $p<0.001$), tiredness (r_{xy}=0.519, $p<0.005$), dizziness (r_{xy}=0.519, $p<0.005$) and lack of concentration (r_{xy} = 0.537, $p<0.005$). Ref. noise annoyance was only correlated to nausea (r_{xy}=0.522, $p<0.005$).
Performance impairment due to low frequency noise exposure was significantly correlated to a feeling of pressure on the head (r_{xy}=0.479, $p<0.01$) and tiredness (r_{xy}=0.479, $p<0.01$). No significant correlation between noise impairment due to ref. noise and symptoms was found.

4. Discussion and conclusions

The results indicate that low frequency noise at levels normally occurring in office and control rooms could negatively influence performance in more demanding tests, while the easier tests remain unaffected. The difference in effects found after low frequency and reference noise exposures support the previous hypothesis [Persson Waye 1995] that different mechanism mediate the effects on performance of low frequency noise compared to higher frequency noise.

The results from the proof reading test where subjects in the low frequency noise made fewer total markings and from the verbal reasoning task, where a longer response time was found in phase B, may be interpreted as a support for the hypothesis that low frequency noise is more difficult to ignore or to habituate to. Less learning in and less habituation to low frequency noise could result in reduced information processing resources available, and lead to a higher competition of available resources, which would interfere with cognitive processing abilities.

The observation that the effects appeared in the second phase of the experiment supports this hypothesis as the effort to cope in low frequency noise would develop over time and thus be more strenuous over time.

In the proof reading test, the tendency to read more lines and make fewer markings could be the result of a coping strategy with the resulting effect of a less thorough treatment of the text material. The longer response time over time seen for the verbal reasoning task is in agreement with previous findings [Persson Waye et al 1997]. In that study, a tendency to longer response time over time was found in the low frequency noise, using the same exposure noises as used in this experiment, but involving a smaller number of test subjects.

Subjects sensitive to LFN generally performed less well and also reported the highest annoyance due to low frequency noise. In other studies, subjects highly sensitive to noise in general have been found to have the lowest performance accuracy during exposure to traffic noise [Belojevic et al. 1992]. Interestingly, this study also showed that the response between the two classification of sensitivity to low frequency noise and sensitivity to noise in general were partly different. Some of these differences were found regardless of noise exposure.

The differences related to noise exposures was the longer response time found in phase B during low frequency noise on the verbal grammatical reasoning task, for subjects sensitive to LFN, while no difference between noise conditions was found using the classification into sensitivity to NG. Differences related to noise exposure were also found for some of the subjective responses like annoyance and perception of control, while this difference was not found using the classification into NG.

If the tendencies that we have seen here are real differences and what the relevance is for effects due to low frequency noise exposure has to bee explored in further studies. The study do however point to the possibility that normally occurring levels in office-like environments with a noise with dominant low frequencies may influence work performance and perception of annoyance and that subjects classified as sensitive to low frequency noise may be at highest risk.

Acknowledgement. The project was supported by funds from Swedish Council for Work Life research (grant nr 1998-06-08) and the project is also part of a network-program for occupational health research funded by the Swedish Working Life Institute. We gratefully acknowledge the valuable research assistance by Agneta Agge and technical assistance by Martin Björkman.

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Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Fulfilling the hand-arm vibration requirements of the EU Machinery Directive

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Summary

The Machinery Directive was written to facilitate the establishment of the single European market by harmonising Member States' health and safety requirements for machinery so eliminating barriers to trade. The Machinery Directive specifies a hierarchy for selection of methods to eliminate risk of accident or ill-health throughout the foreseeable lifetime of the machine. Designers of new machinery are obliged to:

- eliminate or reduce risks as far as possible (inherently safe machinery design and construction);
- take the necessary protection measures in relation to risks that cannot be eliminated; and
- inform users of the residual risks due to any shortcomings of the protection measures adopted, indicate whether any particular training is required and specify any need to provide personal protection equipment.

The Health & Safety Executive (HSE) of the United Kingdom is investigating the hand-arm vibration risks of powered hand-tools and the value of vibration information supplied with the tools. Manufacturers appear to be successfully reducing the vibration emissions of many types of tool. There are many classes of tool that have a wide range in the vibration emissions - frequently up to 4:1 between the highest and lowest emissions in a class. The data provided by manufacturers is likely to provide broad guidance as to which tools are likely to produce the most and least vibration in normal use but often fails to provide an indication of risk.

Hand-arm vibration and the EU Machinery Directive

As with all hazards, the ultimate requirement of the EU Machinery Directive for hand-arm vibration is that the machinery can be used safely. The primary requirement concerning hand-arm vibration is that '... risks resulting from vibrations ... are reduced to the lowest level ...'. There is also a specific requirement to report the hand-arm vibration emission when it exceeds a threshold level of 2.5 m/s^2. If risk has not been eliminated and is present but not evident following these actions then further information about residual risks may be required.

Provision of information concerning residual risk is the last resort in tackling a hazard but it is likely that many instances of reasonable use of hand tools will give rise to hazardous levels of vibration emission. If the vibration information misrepresents the likely vibration risk the manufacturer must alert the purchaser to the residual risk arising during foreseeable use and misuse of the tool.

The data provided by manufacturers features in the practical interface between manufacturer and user duties: the user must ensure that the equipment provided for use at work is suitable. This should include an assessment of the risks from vibration along with other risk assessments. It is reasonable for the user to look to the manufacturer to have fulfilled duties to produce inherently safe equipment and warn of risks that have proved impractical to eliminate.

Verification of state-of-the-art vibration emission

Vibration emissions should not be considered in isolation. Issues such as tool efficiency and the control of hazards other than vibration that affect vibration emission all need to be considered when verifying state-of-the-art vibration emissions. It follows that state-of-the-art vibration emission is not necessarily the lowest vibration emission achieved for a particular type of tool, but is a range of vibration emission levels that is readily achieved by tools in the class. However, the means of verifying conformance with the requirement to reduce risks from vibration to the lowest level has evolved to rely, in the first instance, on a comparison of the manufacturer's reported vibration emission with that of competitors' machinery.

Where the range of vibration emissions in a class is wide, the tool with the highest vibration emission is always open to challenge and tools with emissions above the median for the class will probably have a limited market life.

Evaluation of European Standards for determining vibration emission

A range of vibration test codes have been written for determination of the emission value to be quoted as a requirement of the Machinery Directive. The methods are often included as part of a general safety standard, but also frequently exist as separate supplementary documents. HSE has an ongoing programme to evaluate the ability of Standard vibration emission test codes for:

- generation of reproducible (verifiable) vibration emission values;
- usability and repeatability; and
- indication of likely magnitudes of vibration hazard during normal workplace operation.

The test codes investigated to date have included those written to determine the vibration emissions of various rotary or impulsive action tools from grinders to pavement breakers[3,4,5,6,7,8,9]. New tools were acquired and tested in the laboratory according to the test code. The results were compared with those reported by the manufacturers according to the standard for declaration and verification of vibration emission values[10].

The same tools were then tested under conditions of normal use and the laboratory emissions compared with the workplace emissions.

The relationships between the manufacturer's vibration emission data, the reproduced laboratory emissions and the workplace emissions were then examined[11].

Standards data as a guide to vibration risk

The performance of Standards in relation to the requirements of the Machinery Directive is summarised in Table 1. The standard tests studied are capable of producing a short list of tools likely to include those with the lowest emissions during normal use, but the absolute values quoted often fail to indicate the likely magnitude of the vibration hazard.

Table 1: Performance of Standards in relation to the EU Machinery Directive

Tool	Repeatability and Reproducibility	Verification of manufacturer's emission data according to EN12096	Ranking of emissions in the order found in the workplace	Representation likely workplace magnitude	Verification of risks from vibration reduced to lowest level
Chipping hammers [3]	Satisfactory	9 out of 12	Satisfactory	Requires development	Satisfactory
Rock drills [4]	Satisfactory	7 out of 7	Satisfactory	Variable	Satisfactory
Grinders [5]	Satisfactory	9 our of 13	Requires development	Requires development	Requires development
Pavement breakers & pick hammers [6]	Satisfactory	13 out of 17	Satisfactory	Requires development	Requires development
Impact drills [7]	Variable	8 out of 9	Satisfactory	Requires development	Variable
Sanders [8]	Variable	1 out of 3	Satisfactory	Requires development	Variable
Stoneworking tools & needle scalers [9]	Variable	3 out of 6	Requires development	Requires development	Requires development

Key: **Satisfactory** - the standard is generally **capable** of performing the function
Variable - the standard is **generally satisfactory** but anomalies have been noted
Requires development - the standard is generally **incapable** of performing the **function**

Manufacturer's vibration emission is verified if the subsequently measured emission, a, is less than or equal to the manufacturer's declared emission, $a+K$, using either a declared or an assumed uncertainty value, K[10]. In most cases studied, the manufacturers had declared a single emission value, a, so an assumed uncertainty value, K, must be used according to guidance[10]. The assumed uncertainty can be 50% of the measured level and the real uncertainty can be more! This study verified emission data reported by manufacturer's in 73% of cases, i.e. 1 in 4 emission values could not be verified[11] even after allowing for large test uncertainties.

The risk from vibration can vary greatly from task to task because the vibration emission can be highly variable. Figure 1 shows example 'mean' and 'range' vibration levels during normal workplace use where the highest to lowest vibration varies by more than 3:1. The single Standard test 'emission' values, a, for the chipping hammer and the rock drill clearly fail to represent likely workplace levels - even when the uncertainty, K, is considered. The unusual but real potential for very large uncertainties is demonstrated by impact drill D where the uncertainty is about 10 m/s^2.

Analysis of variance of the results of the emission tests suggests, in general, that if two tools tested at the same laboratory have vibration emission values which have a ratio of 1.2 or less, then they are not significantly different at the 1% confidence level. So, for example, when comparing emission data, a tool with a declared emission of 10 m/s^2 may not in fact be of significantly lower vibration than a tool declared at 12 m/s^2. However, Figure 2 shows that

Standard test emission data can sometimes be used to successfully compare the vibration emissions of tools even if the emission values themselves often fail to represent hazard.

Figure 1. Ranges of vibration magnitudes

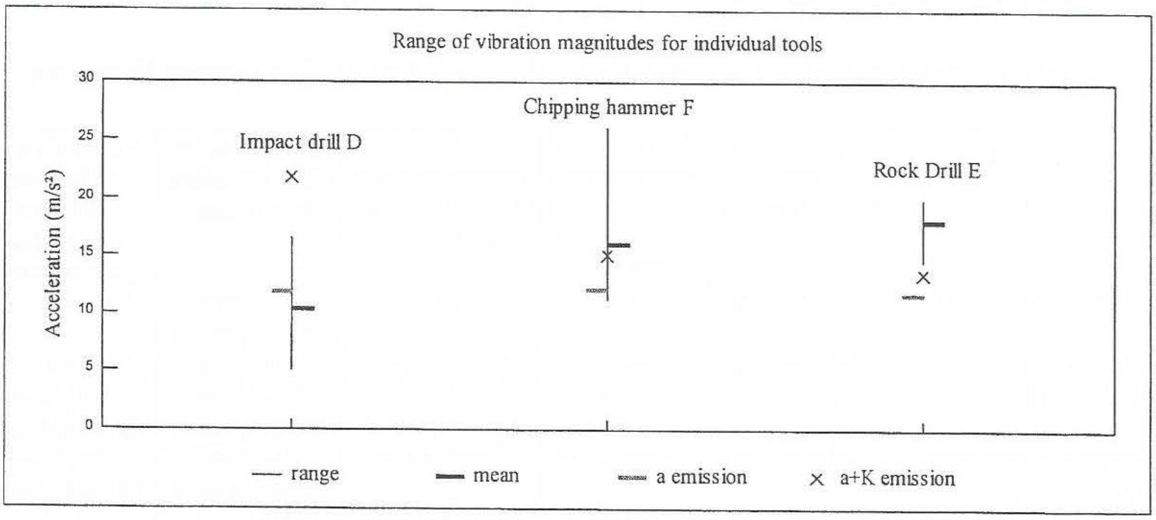

Figure 2. Examples of high and low emission tools

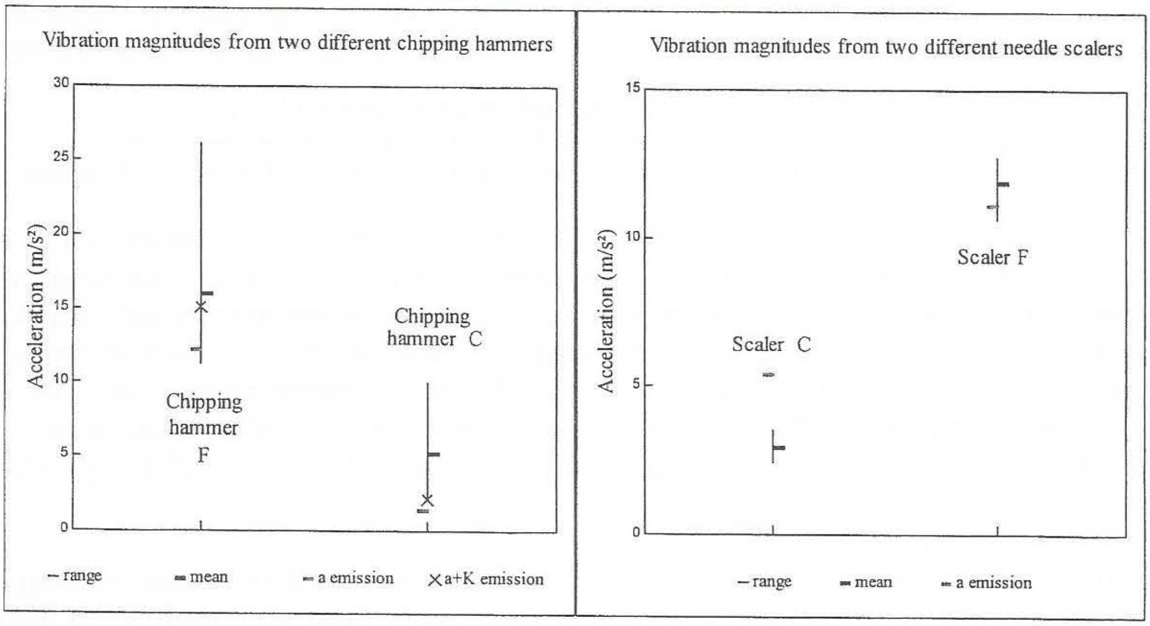

Figure 2 further shows that laboratory test results often fall in the tail of the lowest vibration levels found in conditions of normal use at foundries, construction sites, shipyards, stonemasons' yards, and train and vehicle maintenance depots.

The laboratory levels show that vibration emissions of tools are frequently statistically indistinguishable from one another (Figure 3) as denoted by the checked boxes. Equivalence of vibration emissions is expected to become more common as more tools progress towards state-of-the-art vibration emission levels. It is not clear that current laboratory tests have any advantage over workplace measurements for statistical comparison of emission levels.

Figure 3. Pairs of tools with indistinguishable laboratory derived emission values

Chipping hammers

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	P	R
A																
B																
C																
D																
E	✓															
F																
G																
H		✓														
I																
J																
K			✓													
L				✓						✓						
M						✓										
N				✓						✓		✓				
P							✓									
R	✓				✓					✓						

Impact drills

	A	B	C	D	F	G	H	I	J
A									
B	✓								
C									
D	✓	✓							
F			✓						
G	✓		✓	✓					
H			✓			✓			
I									
J			✓		✓				

Conclusions

A powered hand tool can generate a wide range of vibration magnitudes, perhaps exceeding ±50% of the mean, depending upon its application. This suggests that information to quantify likely risk should not attempt to produce precise single figures.

Vibration emission data has a role to play in verifying that the risks resulting from vibration are reduced to the lowest level. The standards investigated are generally repeatable and reproducible and the majority of examples produce data that indicates the relative risk within broad margins. Manufacturers' data could not be verified for about 1 in 4 cases within margins of up to 50%.

There is a wide range in the vibration emissions between tools in many classes, the ratio of worst to best exceeding 4:1 in some classes. This suggests the potential for reducing vibration risk in the workplace by careful selection of equipment.

Many tools within a class have vibration magnitudes that are statistically indistinguishable from one another either through Standard tests or measurements in the workplace. This is of little concern so long as tools in the same class having much greater or lesser vibration emission are clearly distinguishable from test results.

The results of standardised laboratory tests are inconsistent in their ability to indicate the likely magnitude of workplace vibration hazard. In some cases, the ratio of emission to field vibration underestimates the likely workplace vibration by more than 50%.

Measurements in the workplace under a range of conditions gives a better guide to the magnitude of workplace vibration hazard than do current standard laboratory tests.

Manufacturers need to make measurements under a range of conditions so that they can inform purchasers of the tool of the likely workplace vibration. Such data would appear to fulfill the requirements of the Machinery Directive.

The almost universal failure of Standards to give an accurate indication of workplace vibration hazard leaves the manufacturers with a requirement to explain the vibration risk that is not evident from the data and prevents comparison of data across different classes of tool.

Not only must manufacturers provide information alerting the purchaser to means of controlling the vibration hazard during foreseeable use and misuse of the tool by, for example, providing instructions in the correct usage and limitations of vibration reduction features, but they must also comment on the limited worth of data provided in accordance with CEN vibration test codes as a guide to vibration hazard.

New standards should be written to greatly simplify the vibration testing of powered hand tools. The implied precision of the current tests is misleading to users of the data.

Further work

There are many limitations in the current of standardised hand-arm vibration emission tests. The expected benefits of artificial and laboratory testing have not been realised and disadvantages such as failure to indicate workplace vibration hazard have been introduced. The potential of workplace testing as a means of reporting vibration emissions needs to be revisited. If workplace testing is to be successful, methods for handling relatively large uncertainties found in workplace testing need to be developed and evaluated.

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Advanced hydro-pneumatic semi-active suspension system

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Summary

Automotive suspension design is a compromise brought about by the conflicting demands of ride and handling. The past few years have seen the introduction of increasingly sophisticated, electronically controlled, components into automotive suspensions which redefine the boundaries of the compromise. This paper suggests a simple solution for eliminating discomfort by using advanced hydro-pneumatic semi active suspension system which involves modifications to the twin-accumulator suspension system and conventional passive suspension system without neither excessive cost nor complexity. Moreover, the paper provides a theoretical evaluation for using advanced hydro-pneumatic semi active suspension system suggested, and compares the results obtained to those given by the twin accumulator system and the conventional passive suspension system. As a result the advanced hydro-pneumatic semi active suspension system gives worthwhile improvements when compared to the conventional passive suspension system, and twin accumulator suspension system.

Introduction

The continuously variable damper suspension system is only capable of dissipating energy and the force generation has to be modelled by a rule based strategy. The switching strategies of these systems are based on suspension displacement, suspension velocity, body velocity, frequency content of road input, and vehicle speed. Advances in valve technology have reduced the damper switching times in some of the other recent adaptive systems to such a level that more complex control strategies are now being considered. A number of designs have been proposed, including those by Parker and Lau[1], who describe the development of an electrically controlled floating disc valve fitted to a modified conventional shock absorber, and Doi et al[2] who consider a prototype valve which is placed in the oil flow between a hydraulic actuator and gas spring accumulator. It would be impractical to assume that the response of any valve is instantaneous and therefore first order lag dynamics are used to represent the switching action. The skyhook law is used to introduce the concept of the switchable damper force generator, Karnopp[3] and Charalambous et al[4] which provides a dissipative element for the body cycle and switches off to zero damping in case energy application is required. The continuously variable damper system, sometimes called semi-active, has been described by Sharp and Crolla[5] and studied by Crolla and Aboul-Nour[6], in which the actuator is a continuously variable damper. The damper is theoretically capable of tracking a force demand signal independently of the velocity across the damper[7,8&9]. This paper will considers suspensions employing controllable dampers which, in comparison to the passive systems, represent the simple end of the intelligent suspension spectrum. The system can take various forms but is essentially one in which a damper, its coefficient controlled according to some law, is mounted in parallel with a conventional passive spring. The advanced hydro-pneumatic semi active suspension system is likely to respond to the demand signal by opening or closing orifice. The aim of the paper provides a theoretical evaluation for using advanced hydro-pneumatic semi active suspension system suggested, and compares the results obtained to those given by the twin accumulator system and the conventional passive suspension system.

Modelling of using advanced hydro-pneumatic semi active suspension system (AHPSASS)

Passive suspension system. A standard quarter car model with passive suspension[10] is shown schematically in Figure 1. The passive suspension system is consisting of an accumulator, K_1, in parallel with a valve, C_1. The linearised equations of motion are:-

$$m_w \ddot{X}_1(t) = F_{tyre} - F_{susp} \qquad m_b \ddot{X}_2(t) = F_{susp} \tag{1}$$

Where $F_{tyre} = K_t(X_0(t) - X_1(t))$ (2)

$$F_{susp} = C_1(\dot{X}_1(t) - \dot{X}_2(t)) + K_1(X_1(t) - X_2(t)) \tag{3}$$

Twin-Accumulator Suspension System Model. The twin-accumulator suspension system as shown in Figure2 is consisting of a parallel network of an accumulator, K_2, and a valve, C_2, in series with an accumulator, K_1, this serial network in parallel with a valve, C_1. The linearised equations of motion [11] are:

$$m_w \dot{X}_1(t) = K_t(X_0(t) - X_1(t)) - C_1(\dot{X}_1(t) - \dot{X}_2(t) - K_2(X_1(t) - X_3(t)) - C_2(\dot{X}_1(t) - \dot{X}_3(t)) \tag{4}$$

$$m_b \ddot{X}_2(t) = C_1(\dot{X}_1(t) - \dot{X}_2(t)) + K_1(X_3(t) - X_2(t)) \tag{5}$$

$$K_1(X_3(t) - X_2(t)) = K_2(X_1(t) - X_3(t)) - C_2(\dot{X}_1(t) - \dot{X}_3(t)) \tag{6}$$

where X_3 relative displacement between X_1 and X_2.

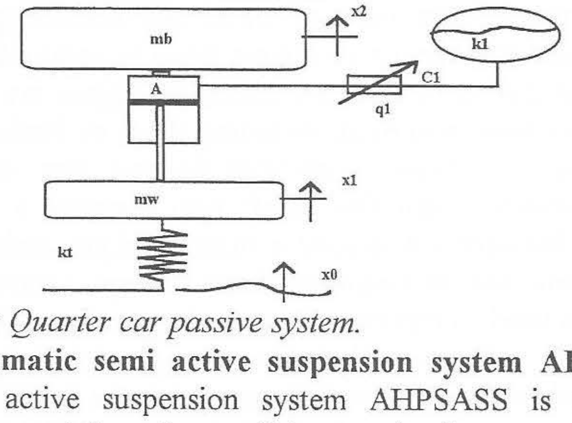

Figure 1: Quarter car passive system.

Advanced hydro-pneumatic semi active suspension system AHPSASS. The advanced hydro-pneumatic semi active suspension system AHPSASS is nearly similar to twin-accumulator suspension consisting of a parallel network of an accumulator, K_2, and a valve, C_2, in series with an accumulator, K_1, this serial network in parallel with a continuously variable damper valve, C_1. However, this system is only capable of dissipating energy and has therefore to be modelled by a rule based strategy. A diagrammatic representation of the quarter car model is shown in Figure 3.

$$m_w \dot{X}_1(t) = K_t(X_0(t) - X_1(t)) - U(t) - K_2(X_1(t) - X_3(t)) - C_2(\dot{X}_1(t) - \dot{X}_3(t)) \tag{7}$$

$$m_b\ddot{X}_2(t) = U(t) + K_1(X_3(t) - X_2(t)) \tag{8}$$

$$K_1(X_3(t) - X_2(t)) = K_2(X_1(t) - X_3(t)) - C_2(\dot{X}_1(t) - \dot{X}_3(t)) \tag{9}$$

$$T_u\dot{C}_a + C_a = C \tag{10}$$

$$U(t) = -(K_{11}X_1 + K_{22}X_2 + K_{33}\dot{X}_1 + K_{44}\dot{X}_2) \tag{11}$$

where K_{11}, K_{22}, K_{33} and K_{44} are control gains and U(t) is the control force.

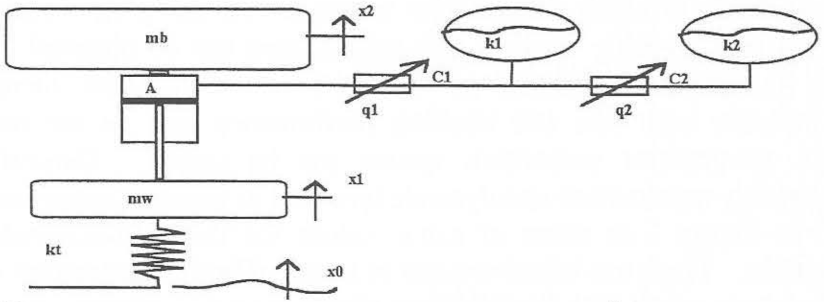

Figure 2: quarter car twin-accumulator system[11].

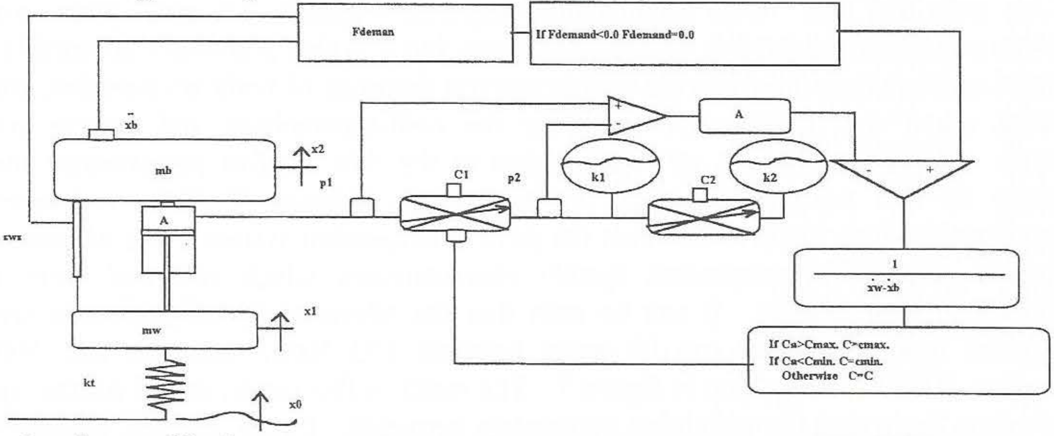

Figure 3: advanced hydro-pneumatic semi active suspension system AHPSASS.

Results

In this section the road surface and suspension models are provided and a procedure for the using AHPSASS. Power spectral density of the ground input profile are represented of the form;

$$S(n) = G / n^{-b} \; m^2 / (cycle / m) \tag{12}$$

This formula, was proposed by Robson[12]. The results established in this paper relate to a vehicle traversing a single road surface at a constant velocity 20 m/s. The quarter car parameters are tabulated in table 1.

Table 1: the quarter car parameters.

Body mass	250 kg
Wheel mass	50 kg
Tyre stiffness	120 kN/m
Cylinder area	$8.0384\ 10^{-4}\ m^2$
Springs stiffness	18 kN/m
C, Ns/m	600, 1200, 1800, 2400 and 3000

The power spectral densities are obtained in Figure 2, for the twin-accumulator suspension system, which contains two accumulators gas springs and two throttle valves dampers which represent the suspension system. Figure 4 indicates the spectral densities of the weighted body acceleration, the suspension working space and the dynamic tyre load for the twin accumulator suspension system at different damping coefficient by adjusting the First throttle valve (C_1) has been presented. This figure, indicates increase in an improvement in the performance around the body and wheel resonance frequencies as a result of increasing the damping coefficient, C1. While, a worth improvement exists in the frequency range from 1.5-8 Hz in both the body acceleration and dynamic tyre load. Tables 2 and 3 summarises the r.m.s. values of body acceleration, suspension working space and dynamic tyre load for a twin accumulator suspension at stiffness 18 kN/m and different values for the damping coefficient, C1 and C2. Summaries from these results, the best ride performance can be obtained by adjust the first damping first accumulator. Moreover, the selection of the first damping must be a compromise between both ride and handling performance, and so the benefit from using advanced twin accumulator suspension system can be gained. Generally speaking, the improvement in body acceleration and dynamic tyre load at constant suspension working space are presented in Figure 5 in terms of r.m.s. values for the twin-accumulator and passive suspension systems. There are improvements in terms of body acceleration and dynamic tyre load when using twin-accumulator suspension system than the passive suspension system. It can be seen that the twin accumulator suspension system not only gives worthwhile improvements over the passive suspension system, but it is also practically acceptable. Figure 6 shows a comparison between the power spectral densities of body acceleration, suspension working space and dynamic tyre load for the twin-accumulator and passive suspension systems. Obviously, there is an improvement in the ride comfort performance over those obtained for the passive suspension system. This indicates that the twin-accumulator suspension system is better in use than the passive suspension system. The advanced hydro-pneumatic semi-active suspension system characteristics which recorded from the PC-Computer in time domain. It can be seen that the advanced hydro-pneumatic semi-active suspension system settings can be made between 300 Ns/m minimum and 5000 Ns/m maximum. This is clearly seen in Figure 7. The result in this paper, are of course, specific to the random input and the weighting parameters extracted. Power spectral density functions and the root mean square values r.m.s. are calculated when the time delay 20 ms and time dead 10 ms are considered. Figure 8 presents the advanced hydro-pneumatic semi-active suspension system characteristics which recorded from the PC-computer in time domain. It can be seen that the setting can be made between min. and max. values. The result for the passive and the advanced hydro-pneumatic semi-active and passive suspension systems are calculated in time domain and converted to power spectral densities using FFT fast furrier transformation. Figure 9 shows the power spectral densities of body acceleration, suspension working space and dynamic tyre load for the passive and the advanced hydro-pneumatic semi-active suspension systems. This figure indicates that there are worthwhile improvement in ride comfort, suspension working space and dynamic tyre load for advanced hydro-pneumatic semi-active suspension system particularly at the sprung mass resonance. It is clearly seen that there is an improvement in the peak of body response, despite there is a deterioration in the response around the wheel mass response in term of body acceleration. A summary of the results for passive, twin accumulator and advanced hydro-pneumatic semi-active suspension systems in terms of r.m.s. values are shown in Figure10. This figure shows the relationship between the body acceleration and dynamic tyre load variations at constant working space. The advanced hydro-pneumatic semi-active suspension system gives the best performance of all the systems compared.

Conclusions

In this paper, the performances of various competing suspension concepts are compared theoretical. Quarter car simulations were used to investigate fundamental differences in the way different systems controlled the essential aspects of ride dynamics known as body bounce and wheel hop. In this work advanced hydro-pneumatic semi-active suspension system is studied to achieve optimum ride with low energy dissipation. A significant improvement in ride performance can be obtained with advanced hydro-pneumatic semi-active suspension system compared with a passive, and twin accumulator suspension system

Table 2: r.m.s. for the twin-accumulator suspension system.

First valve Ns/m, C1	ACC, m/s^2	SWS, cm	DTL, N
600	1.37	2.89	931
1200	1.67	2.17	786
1800	1.98	1.8	789
2400	2.26	1.56	836
3000	2.52	1.39	898

Table 3: r.m.s. for the twin-accumulator suspension system.

Second valve Ns/m, C2	ACC, m/s^2	SWS, cm	DTL, N
600	1.64	2.27	793
1200	1.67	2.17	786
1800	1.69	2.1	786
2400	1.7	2.05	788
3000	1.71	2.02	791

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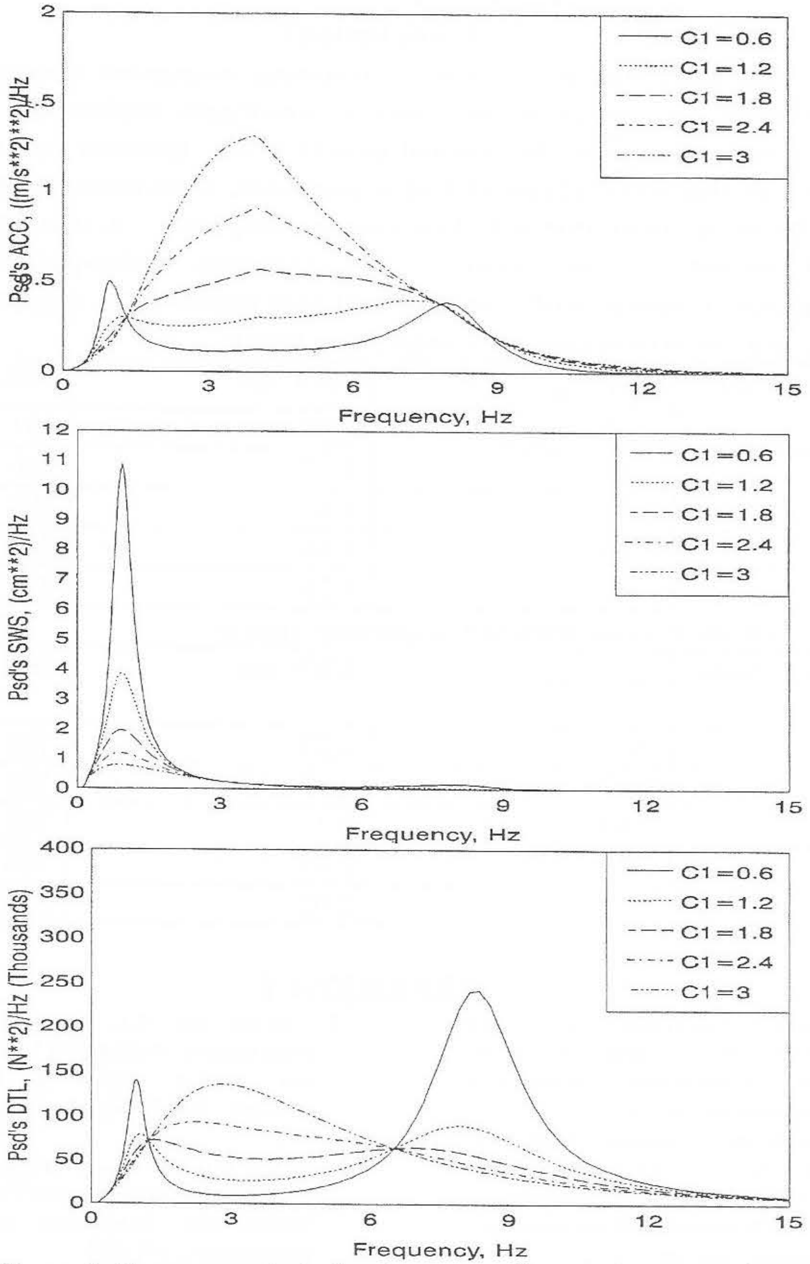

Figure4: Power spectral density curves for a twin accumulator suspension system with a spring stiffness of 18 kN/m and second damping coefficient 1.2 kNs/m.

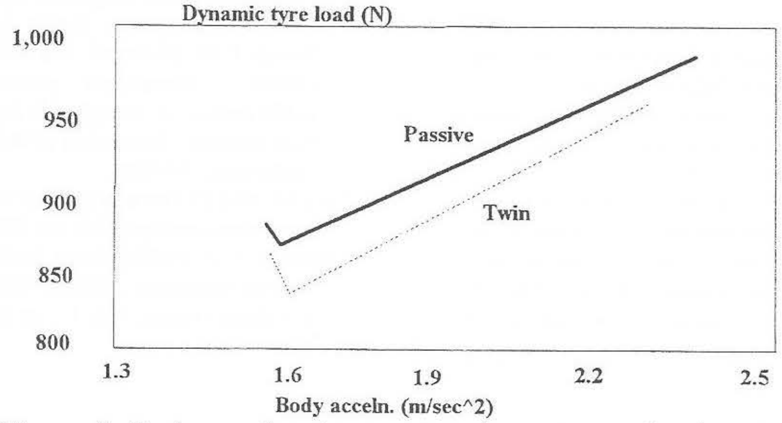

Figure 5: Body acceleration against dynamic tyre load variation

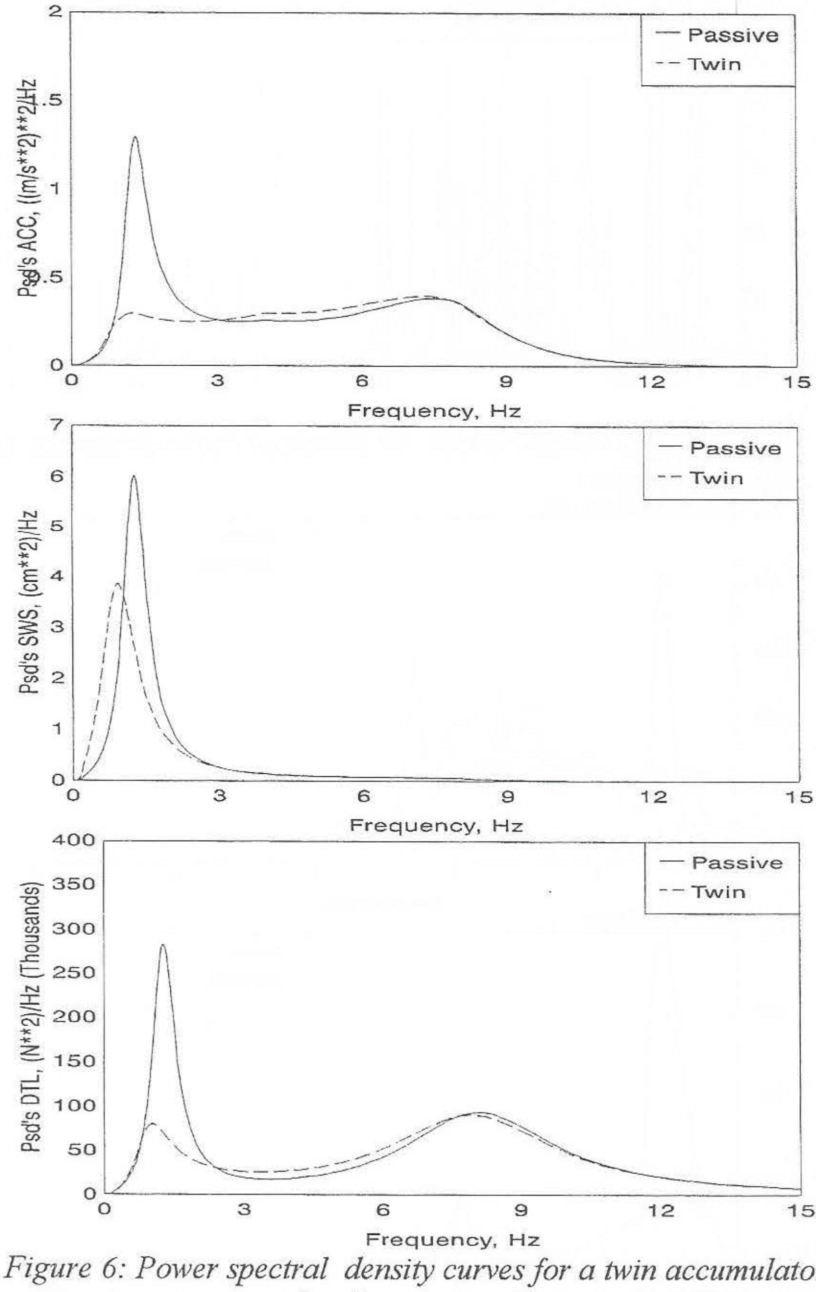

Figure 6: Power spectral density curves for a twin accumulator and passive suspensions system with a damping coefficient of 1.2 kNs/m and spring stiffness of 18 kN/m.

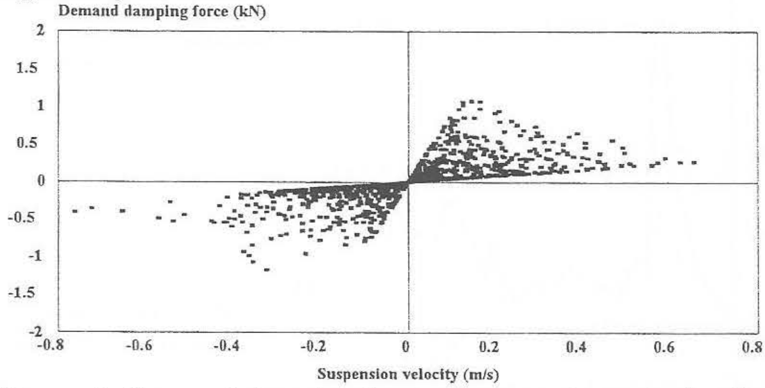

Figure 7: Demand damping force v. suspension velocity diagram.

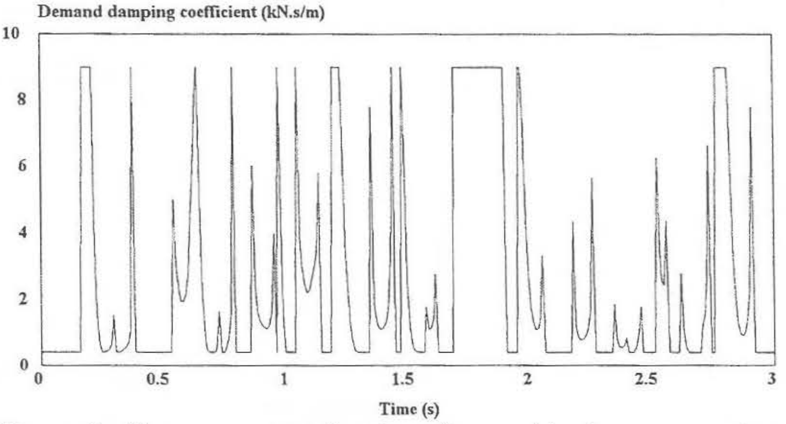

Figure 8: The current set for the advanced hydro-pneumatic continuously variable damper.

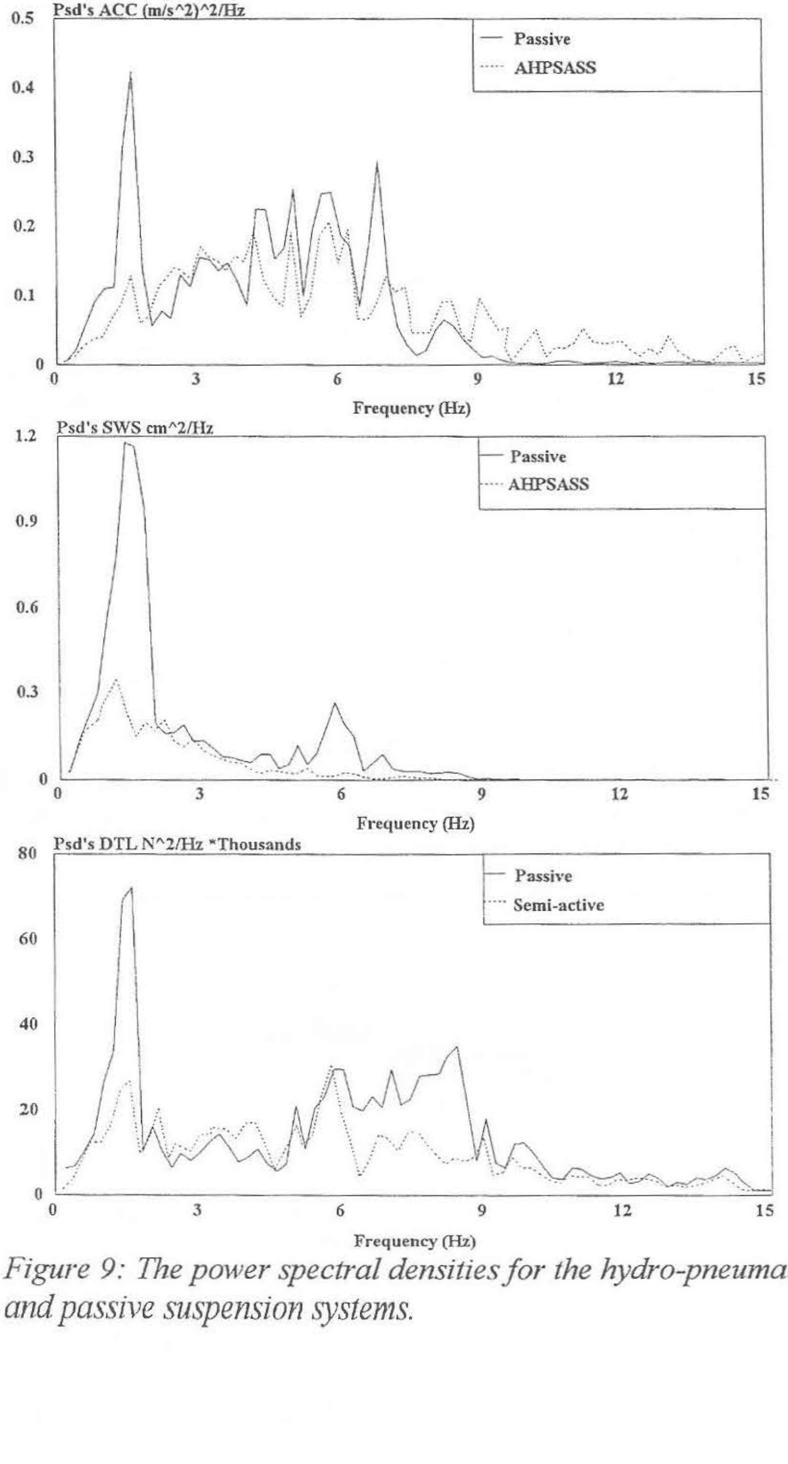

Figure 9: The power spectral densities for the hydro-pneumatic semi-active and passive suspension systems.

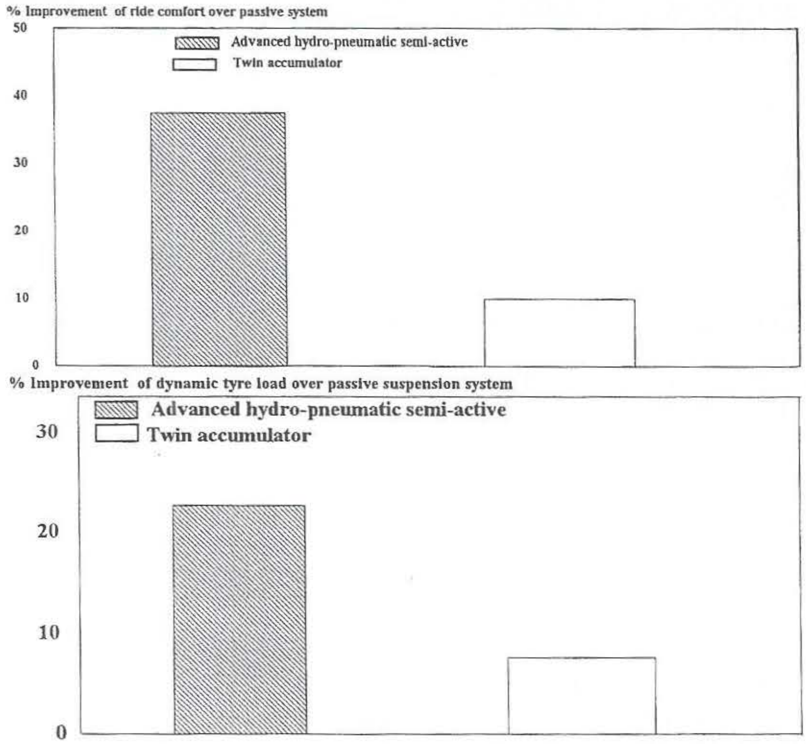

Figure 10: Percentage improvement of body acceleration and dynamic tyre load for twin accumulator and advanced hydro-pneumatic suspension systems over passive suspension system.

Notation

S(n)	Displacement power spectral density $m^2 / (\text{cycle} / m)$.
G	Road roughness coefficient $m^2 / (\text{cycle} / m)^{n-1}$
n	wave number cycle/m.
b	an exponent.
Psd's ACC	power spectral density of body acceleration $(m / \sec^2)^2 / Hz$.
Psd's SWS	Power spectral density of suspension working space m^2 / Hz.
Psd's DTL	Power spectral density of dynamic tyre load N^2 / Hz.
X_0	Road roughness displacement m.
X_1, X_2	Wheel displacement and body displacement respectively m.
C_1 and C_2	First and second damping coefficients N.sec/m.
M_w, M_b	Wheel and Body masses kg.
A	Strut area m^2.
k_1 and k_2	First & second gas spring stiffnessN/m.
k_t	Tyre spring stiffness N/m.
q1and q2	Flow rate throughout the valves.

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Proceedings edited by
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The Deelen Infrasound Array for recording sonic booms and events of CTBT interest

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1. Abstract

The Seismology Division of the Royal Netherlands Meteorological Institute (KNMI) has build up expertise in infrasound measurements by investigating low frequency events in order to distinguish between seismic and sonic events. KNMI operates, amongst others, a sixteen element microbarometer array with an aperture of 1.5 km, the Deelen Infrasound Array (DIA). Sonic booms and events of Comprehensive Test Ban Treaty (CTBT) interest are recorded within the frequency range of 100 seconds and 40 Hertz. Recently, KNMI and Microflown Technologies B.V. started a collaboration concerning infrasound measurements. This paper reports the use of a novel sensor. The so-called Microflown [1] is an acoustic sensor, sensitive for frequencies from 0Hz up to 1kHz. The Microflown is developed at the University of Twente and commercialised by Microflown Technologies B.V [3].

2. Introduction

Recently, the significance of infrasound measurements has been established in the Comprehensive Test Ban Treaty (CTBT) as a technique to detect and identify possible nuclear explosions. For this purpose a world-wide network of 60 infrasound arrays is presently being constructed. KNMI operates since 1999 an experimental array in the Netherlands. The Deelen Infrasound Array (DIA) consist of in house developed microbarometers, based on a differential pressure sensor. Detailed array response calculations have resulted in a omni-directional sensitive array configuration. Efficiently discriminating between infrasound events and noise, is done with a detector based on Fisher statistics. Characteristic values like apparent sound velocity and azimuth, can be derived. Including the data of two other small arrays (aperture of 100 meters) results in an accurate event location, through cross-bearing, and origin time.

Pressure variations consist of compression and dilatation with a certain frequency. The frequency is resolved by the Microflown through the frequency of the induced temperature differences. The Microflown has advantages, which are tested together with KNMI for infrasound applications, compared to microbarometers and pressure microphones. The Microflown has no moving parts, which make it very reliable. Resonances do not occur. Given its underlying thermal principle, the self drying Microflown is moisture resistant and it is made from inert materials (platinum, silicon) so no corrosion problems can occur. All materials used are corrosion resistant and sustain high temperatures.

3. The Deelen Infrasound Array

In general, an array is a number of instruments which is, through its layout, able to detect signals and localise the incoming direction of energy. The array configuration controls the resolution of the array. An optimal array is equally sensitive to all infrasonic signals, independent of incoming angle and direction. Array design and calculations are based on signal coherency. The optimal array is capable of homogeneously sampling the surrounding atmosphere [4]. Figure 1 displays the layout of the 16 microbarometers and corresponding response. To each microbarometer six porous hoses are connected in star configuration to reduce noise. The circular response implies an optimal array.

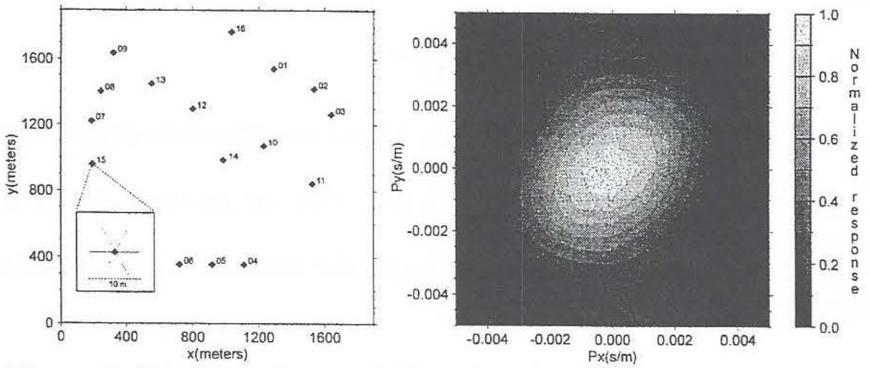

Figure 1: DIA array layout (left) and corresponding response (right)

4. Infrasonic signals

Sources of infrasound emit pressure fluctuations between 500s and 40Hz. Examples of infrasonic sources are: planes flying through the sound barrier, meteors entering the earth's atmosphere, volcano explosions, nuclear explosions etc. Wind causes noise within the same frequency band, between 1 up to 10 Hz. Figure 2 shows two examples of infrasound record by the 16 microbarometers. A high frequent sonic boom on the left and a low frequent meteor detection ant the right.

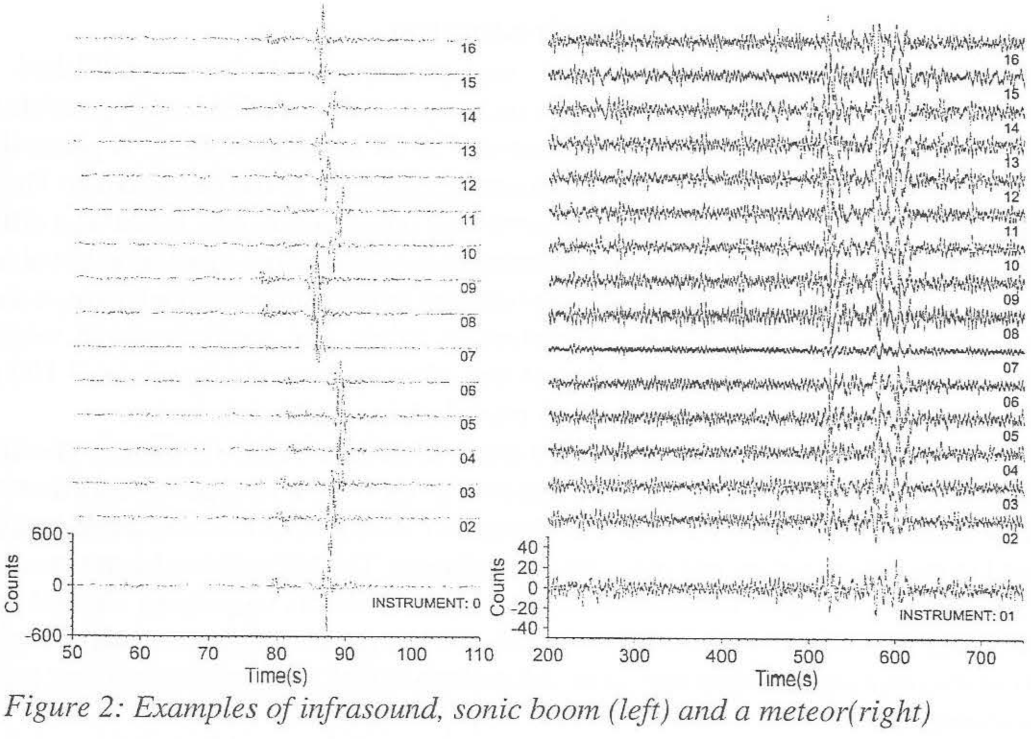

Figure 2: Examples of infrasound, sonic boom (left) and a meteor(right)

5. Data processing: frequency slowness analysis

As proposed by [5], data processing at KNMI is done on the basis of a frequency slowness, being the inverse of apparent sound velocity, analysis combined with Fisher statistics. Frequency domain processing, in stead of conventional time domain, enables the development of detection tools by making use phase, amplitude, frequency and coherency characteristics. Figure 3 shows the result of the frequency domain processing. The top frame displays the best beam or the summed signal with azimuth and velocity for which the maximum coherency is found. Coherency is plotted in the middle frame as Fisher value (which is a scaled signal to noise ratio). Clearly, coherence increases around the meteor detection. The secondary arrival is more low frequent, combined with its delay time with respect to the first arrival, a probable thermospheric reflection is seen [6]. Resolved angles are plotted in the lower frame. The meteor energy is coming from the North-east while other coherent signal seems to come form more North-western angles.

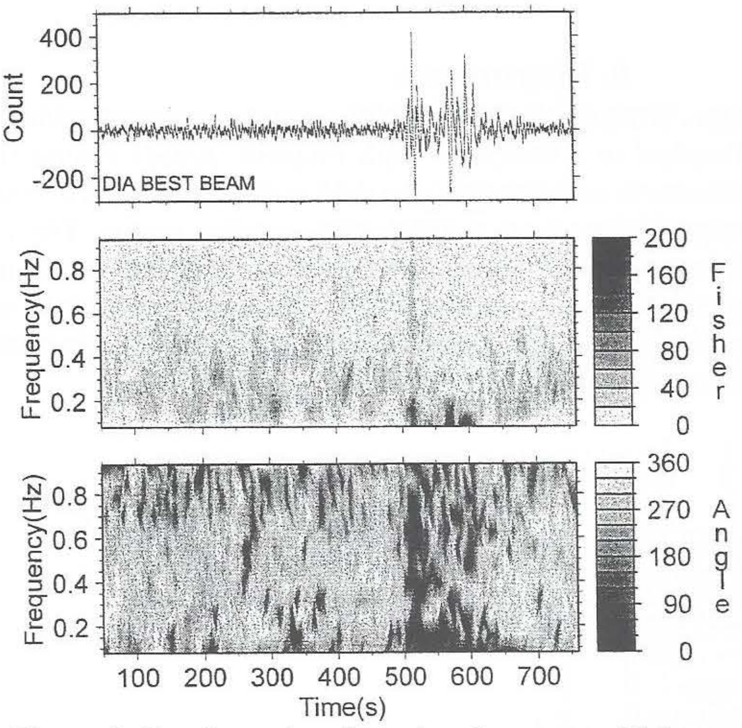

Figure 3: Best beam (top frame), coherency or Fisher value(middle frame) and resolved angle (bottom frame) for the meteor signal (right in Figure 2)

Results from detailed frequency slowness analyses of the two sources of infrasound shown in Figure 3, are displayed Figure 4. Frequency slowness power can be interpreted as a shifted array response due to the phase differences of the signal travelling over the array. The highest values of the fp-power correspond to the value for slowness for which the signal is best resolved. The meteor energy in the right frame is coming from 82 deg East. A storm depression on the Atlantic ocean generated standing waves in the ocean. These standing waves create low frequent signal, so-called microbaroms, through its atmospheric coupling. This energy comes from the North-west with respect to the array and is shown in the left frame of Figure 4.

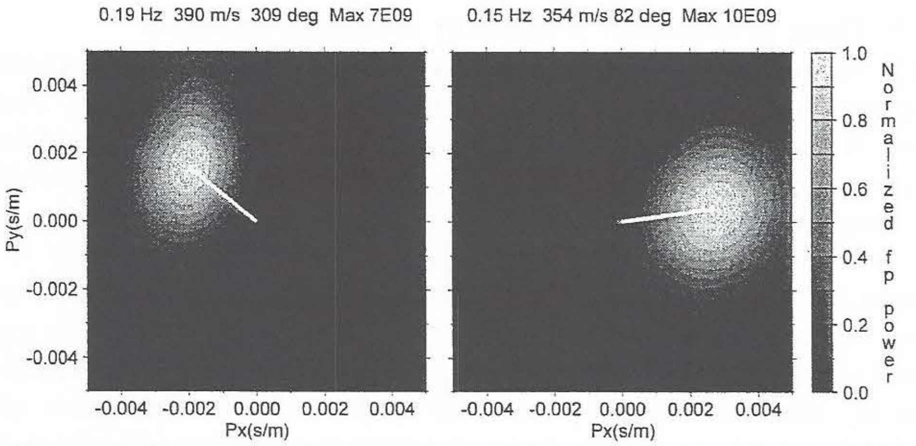

Figure 4: Frequency-slowness power plots. The vector denotes the resolved apparent sound velocity by its length and resolved azimuth by its angle with respect to the North.

6. Instruments

6.1 The KNMI microbarometer. When developing an infrasound sensor one can either choose to make a microphone low frequent or a barograph high frequent. KNMI choose the later approach for amongst others robustness with respect to the field applications. Figure 5 shows the in house developed microbarometer based on a differential pressure sensor. The pressure fluctuations are measured with respect to the backing volume. Doing so, one would also measure very low frequent meteorological pressure variations. Therefore, a thin capillary is included within the backing volume, as a leak. Through its acoustical resistance, the capillary controls the low frequency cut-off of the microbaromter, being 500 seconds.

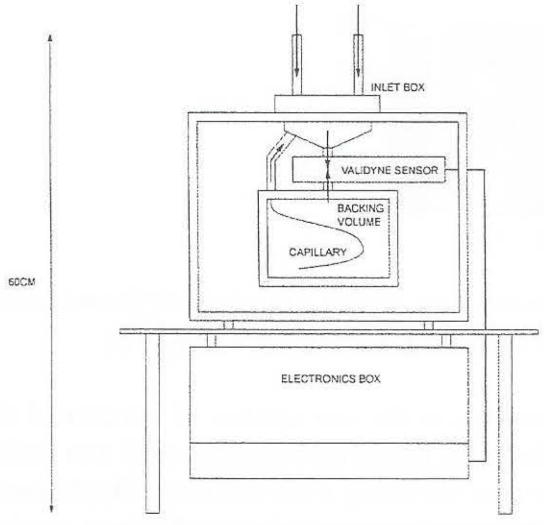

Figure 5: Schematic drawing of the KNMI microbarometer based on a differential pressure sensor.

6.2 The Microflown. The Microflown is a silicon-based sensor that is fabricated in a cleanroom. It is in fact a highly sensitive mass flow sensor (a sensor that is designed to detect DC flow) made in such way that it has a very fast response time. The result is an acoustic sensor that is capable of measuring the particle velocity from DC (0Hz) up to 1kHz with a flat frequency response and with a high signal to noise ratio. The polar pattern or directivity is a figure of eight at all frequencies.

Since its invention in 1994 it is mostly used for measurement purposes (1D and 3D-sound intensity measurement, or acoustic impedance. The Microflown is also used for measuring DC flows. DC flow is in fact particle velocity with a frequency of 0Hz. Nowadays sound-energy determination and three-dimensional impulse response are under investigation [2], [3]. The Microflown is capable of measuring particle velocity in stead of sound pressure, closely related to the pressure gradient. So in an audio perspective the Microflown can be seen as a pressure gradient microphone (with a figure-of-eight directivity pattern) having a high signal to noise ratio from 0Hz up to 1kHz. For frequencies higher than 1kHz the frequency response has a decay of –6dB/oct. The Microflown itself consists of two very closely spaced thin wires (spacing 350μm) of silicon nitride with an electrically conducting platinum pattern on top of them. A SEM photograph of a Microflown is depicted in Figure 6. The size of the two wires is 1000×10×0.5 micrometer (l×w×h). The metal pattern is used as temperature sensor *and* heater. The silicon nitride layer is used as a mechanical carrier for the platinum resistor patterns. The sensors are powered by an electrical current, causing the sensors to heat up. The temperature difference of the two cantilevers is linear dependent on the particle velocity. The two squares S1 and S2 in Figure 7 represent the two temperature sensors of the Microflown. The temperature sensors are implemented as platinum resistors and powered by an electrical current dissipating an electrical power P_{el}, causing it to heat-up, leading to a typical operational temperature of about 200°C to 400°C. When the temperature of the sensors increases the resistance will also increase. When particle velocity is present, it alters the temperature distribution around the resistors. The temperature difference of the two sensors quantifies the particle velocity. When no particle velocity is present all the heat is transferred in the surrounding air ($q_{stat.}$). When particle velocity is present a convective heat transfer of both sensors ($q_{conv1\&2}$) will cause a temperature drop of both sensors. The upstream sensor however, will drop more in temperature than the downstream sensor since the downstream sensor is heated by the upstream convective heat loss ($q_{conv.}$), see Figure 7. A temperature difference will be the result. The temperature difference is proportional to the particle velocity. Not all the convective heat loss of S_1 will be transferred to S_2, a certain percentage (ξ) will be lost. This percentage will rise if the sensors are positioned further apart from each other. If, on the other hand, the sensors are brought closer together another phenomenon will become dominant. The particle velocity induced temperature difference will cause a conductive heat flow in the opposite direction. This feedback heat flow will temper the sensitivity. The closer the sensors are placed, the more conductive heat flow will take its effect. Several temperatures of the two sensors of the Microflown are shown in Figure 8. Due to the thermal mass of the sensors, after 1kHz the sensors cannot follow the thermal signal. The Microflown exhibits a –6dB/oct high frequency roll of because of this.

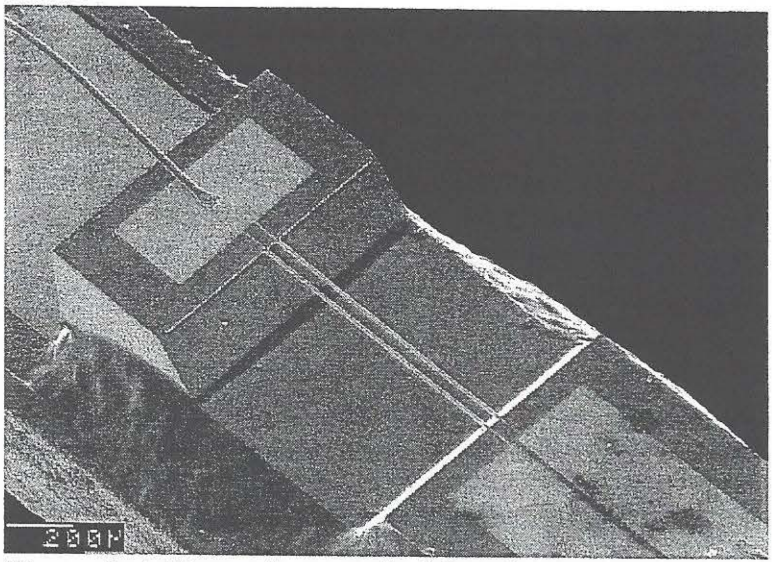

Figure 6: A Photo of a part of a Microflown.

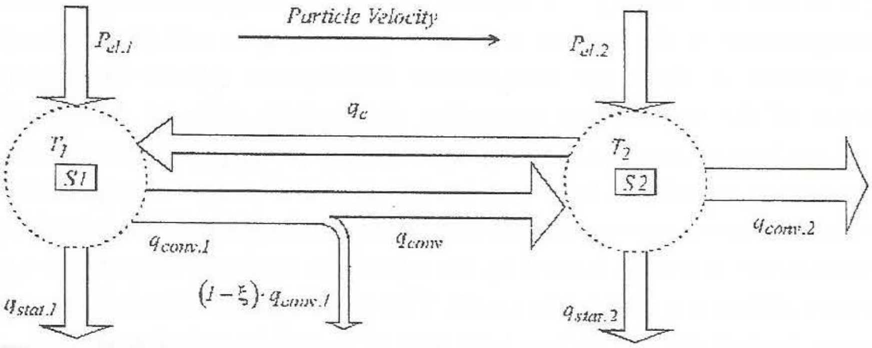

Figure 7: Schematic overview of the heat flows around a Microflown.

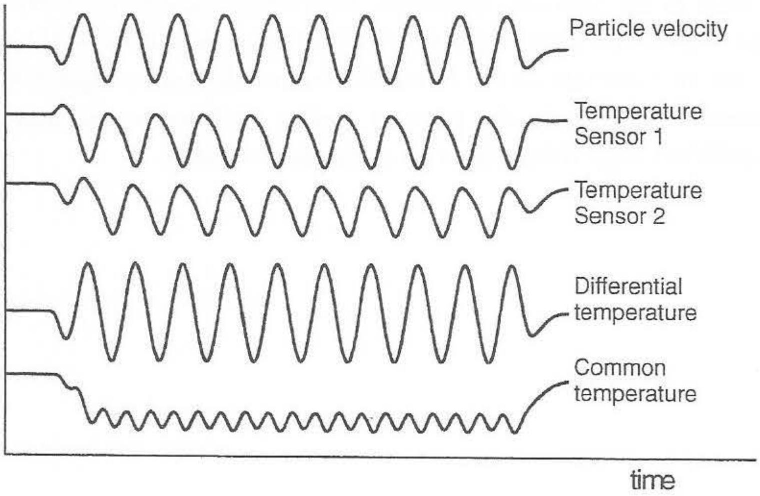

Figure 8: The (measured) temperatures of the Microflown as result of a particle velocity wave. A particle velocity wave will cool down both sensors in a different manner. The difference signal of both sensors represents the particle velocity and the sum (the common signal) the cooling down.

7. Measurements

7.1 The Microflown without a (wind) noise reducing mounting. With the use of a 12" loudspeaker a 20Hz sine tone was generated. Signals and noise levels of the microbarometer and the Microflown were compared. The distance between the loudspeaker and the transducers was 50cm. Furthermore the on- and off axis output of the Microflown was measured. The output signals of the Microflown and the microbarometer were respectively 85mV and 20mV, their noise levels about 0.2mV and 2mV. A rough estimation would be that that the signal to noise ratio of the Microflown is about 30dB higher than the microbarometer. The lateral reduction at 20Hz was measured 40dB. The measurement was performed by rotating the Microflown and in a normal room.

7.2 The Microflown with a (wind) noise reducing mounting. The Microflown is a particle velocity sensitive microphone. It is therefore very sensitive for wind (even more than pressure sensors). Two ways of reducing wind have been tested. First we mounted foam in front of both inputs of the Microflown. This resulted in a reasonable reduction of the wind noise for an open structure foam. A more dense foam reduced the wind noise more but also damped the sensitivity. The Microflown was tested outdoors overnight under rather windy and rainy conditions. Although the Microflown itself showed no physical damage, the noise reduction appeared insufficient.

Another attempt showed more promising results. At one input of the Microflown a closed rigid tube was mounted and at the other a flexible tube was mounted. A *sound pressure* wave would deform the flexible tube and not the rigid one, inducing a particle velocity inside the mounting. This way of noise reducing will make the set up sensitive to sound pressure in stead of particle velocity; the directivity properties of the Microflown will therefore be lost. The rigid tube will act as backing volume. We used a volume of 0.6l. We expect the system to measure lower frequencies if the backing volume is enlarged. Opening the door of the lab resulted in signals shown in Figure 9. Despite the difference in transducing, the general trend of the signal is similar. The "noise" seen on the Microflown is due to electronic interference, it is not selfnoise. The flexible tube is used as a pressure to particle displacement converter. We expect a higher sensitivity and a better noise reduction when the length of the tube is increased.

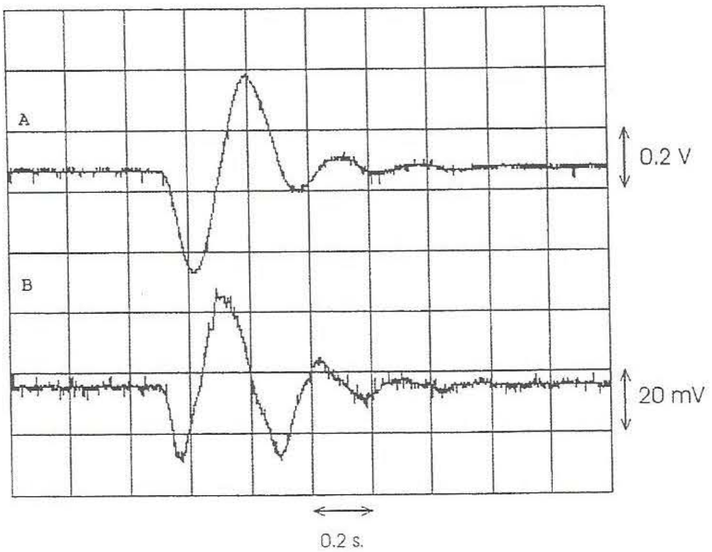

Figure 9: The measured signals of a microbarometer (A) and a Microflown (B) as result of a atmospheric distortion in a room with a volume of 144m^3.

8. Conclusions

The Deelen Infrasound Array is capable of detecting and localising infrasound. Identification of different sources of infrasound occurring in the same frequency band is possible with the high resolution array (p.e. microbaroms, sonic booms and meteors). Experiments with the Microflown have shown promising results, as low noise, directional and particle velocity sensor. Proven durability in the field and developments to obtain a proper low frequency cut-off, will allow the Microflown to be a highly competitive infrasound sensor.

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Unpleasantness and acceptable limits of low frequency sound

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Summary

Equal unpleasant sound pressure levels of pure tones from 10 Hz to 500 Hz were obtained by the method of adjustment in which subjects adjusted sound pressure levels equating to subjective degrees of unpleasantness on a 4-steps rating scale. In addition, the maximum acceptable sound pressure levels were measured on each frequency, assuming four types of situations, that is, living rooms, bedrooms, offices and factories. It was found that the acceptable limits were equivalent to the very low levels of unpleasantness in some situations. And the third-order polynomial models of physical variables were well fitted to the subjective response data.

Introduction

In the evaluation of low frequency noise, the terms "loudness" and "annoyance" are often used to represent the overall subjective evaluations of noise. In several former studies, it was reported that there was some difference between loudness and annoyance judgments in the case of low frequency noise. On the other hand, a recent work (Kuwano, Fastl and Namba[1]) reported as follows. "It was found that the impressions of loudness, annoyance and unpleasantness of synthesized sounds are similar to each other and mainly determined by loudness level… On the other hand, in the case of recorded road traffic noise, there was some difference between loudness and annoyance judgments." They suggested that the difference might be resulted from aesthetic and/or cognitive aspects of the sound. In our former studies, however, it was found that not only loudness, but also oppression and vibration feelings are dominant responses of even synthetic sound in low frequency range noise. And unpleasantness was considered as one of the most representative responses of these negative feelings (Nakamura and Inukai[2]). The purpose of this study is to obtain equal unpleasantness contours and acceptable limits for different situations, and to compare them with equal loudness contours which appeared in the former research work (Lydolf and Møller[3]).

Method

Stimuli. The stimuli presented were pure tones at 1/3octave frequencies in the range from 20Hz to 250Hz and 500Hz.

Subjects. Paid volunteers, 27 female and 12 male, with ages ranging fro subjects, aged between 19 and 62 participated in this study.

Apparatus. The experiment was carried out in a newly constructed 22.75 cubic meter pressure- field chamber (3.5 x 2.5 x 2.6 m). The chamber was constructed in concrete and sixteen 46-cm diameter loudspeakers mounted in the wall and driven by sixteen 150 W amplifiers. The background noise level of the new chamber was improved to be less than 16 dB(A). Absorption rates were 0.6/125 Hz and 0.95/500 Hz. There was a small char to sit on for a subject. The stimuli were generated with a sine/noise generate (B&K 1049) and presented to subjects through the 16 loudspeakers in the chamber. Their levels were produced by subjects by manipulating a remote main volume controller of the power amplifiers. The controller can set levels of stimuli at within 1 dB steps. Sound pressure levels were measured by the microphone in the chamber as shown in Figure 1 and calibrated at the position of subject's head.

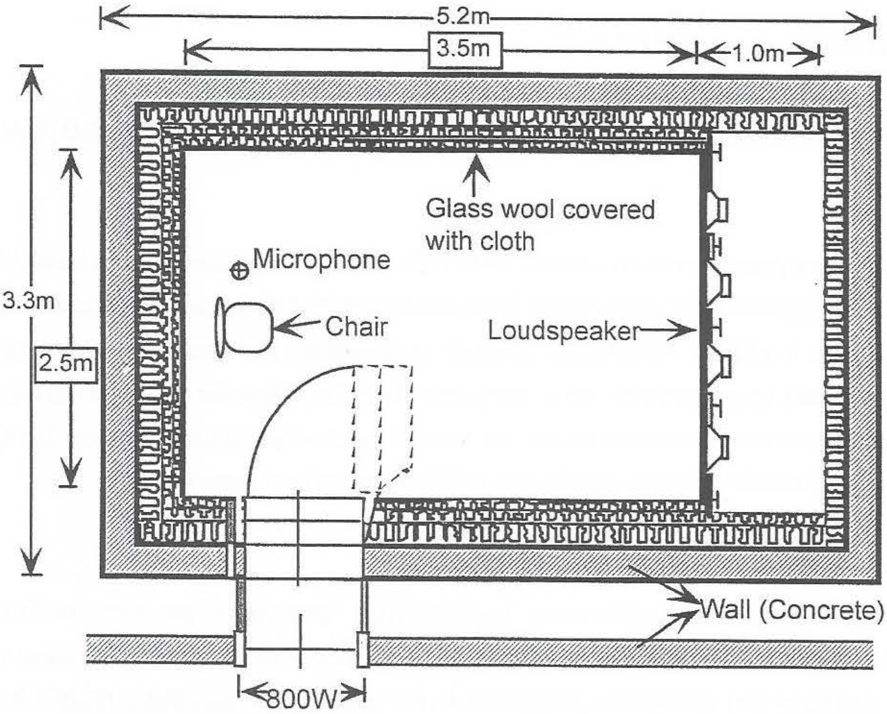

Figure 1:Top view of the pressure-field chamber used for the experiment. The height in the chamber was 2.6 m.

Levels of unpleasantness. The 4 levels of unpleasantness were defined on 5 points rating scale. The scale points were labeled verbally as shown in Figure 3.

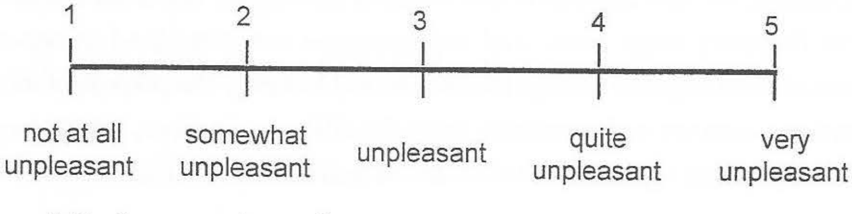

Figure 2: Unpleasant rating scale.

Procedure. Subjects were required to produce a level of a given stimulus, which reflects their subjective unpleasantness by manipulating the volume controller. The produced level was adjusted by subject to represent a given grade number on the rating scale. The category numbers were 2 (=somewhat unpleasant), 3 (=unpleasant), 4 (=quite unpleasant), 5 (=very unpleasant) which were designated by the experimenter to subjects in each experiment.

Results and discussion

Threshold, equal unpleasantness levels and acceptable maximum limits of SPL. Observed sound pressure levels were averaged over subjects for each rating grade and hearing threshold. The Figure 3 shows the obtained mean values as symbols: ■ ▲ ● ♦. Averaged sound pressure levels of acceptable maximum limits were also calculated over subjects for each living situation. And their values are shown in Figure 3, by symbols: ○ • –. Their standard deviations are indicated as smaller symbols, at the bottom of the figure.

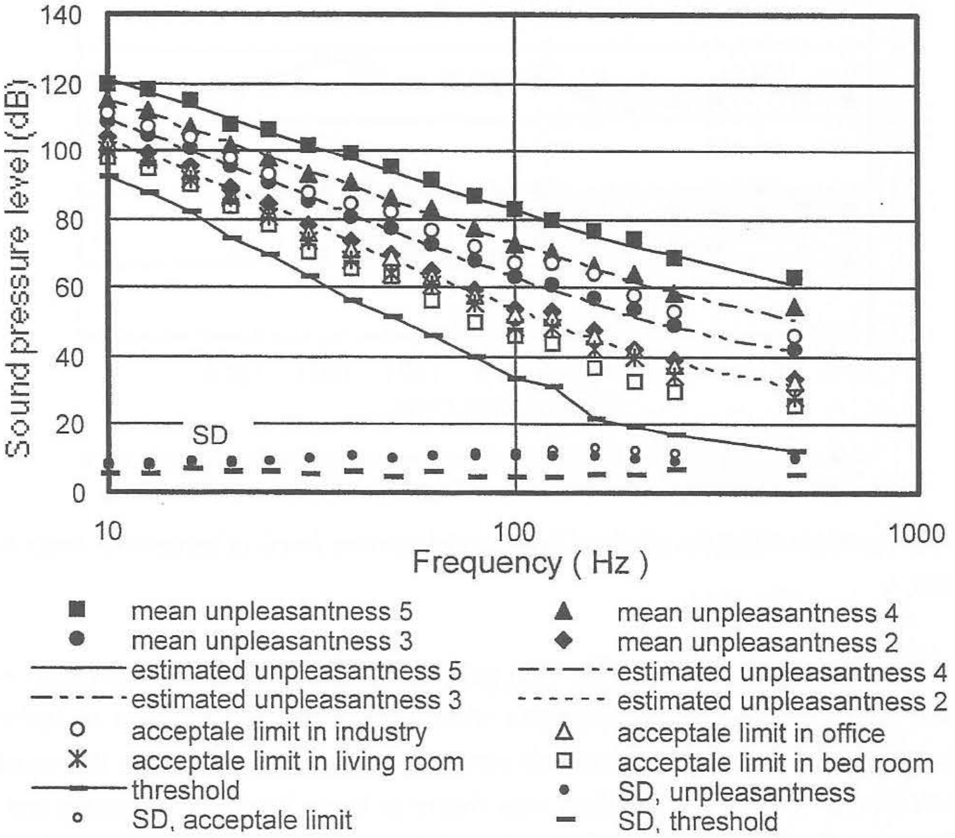

Figure 3:Equal unpleasantness contours and acceptable limits of sound pressure levels for different living situations.

Prediction of equal unpleasantness contours. Parameters of prediction formula of unpleasantness ratings, y 's were estimated by fitting following polynomial equation to the data.

$$y = (0.312 - 0.176x + 0.0360x^2)\,L - 43.5 + 37.4x - 10.7x^2 + 0.988x^3, \tag{1}$$

Where L means sound pressure level in dB (L) at frequency h and x means the logarithm of frequency h. The goodness of fit was shown by adjusted $R^2 = 0.988$. Then, in order to obtain equal unpleasantness contours, equation (1) was transformed to equation (2). The estimate of sound pressure level (L) for a

$$L = [y + 43.5 - 37.4x + 10.7x^2 - 0.988x^3] / (0.312 - 0.176x + 0.0360x^2), \tag{2}$$

given unpleasantness rating grade (y) was circulated by equation (2). The estimated equal unpleasantness contours were shown as four types of curves in Figure 3.

Relations between unpleasantness levels and acceptable maximum limits. Unpleasantness ratings of acceptable limits were estimated by substituting their sound pressure levels in the formula (1). Obtained estimates of unpleasantness ratings were shown in Figure 3. The figure showed that the unpleasantness ratings of acceptable limit levels were constant to a given situation over different frequencies. On the other hand, the unpleasantness ratings were different depending on situation.

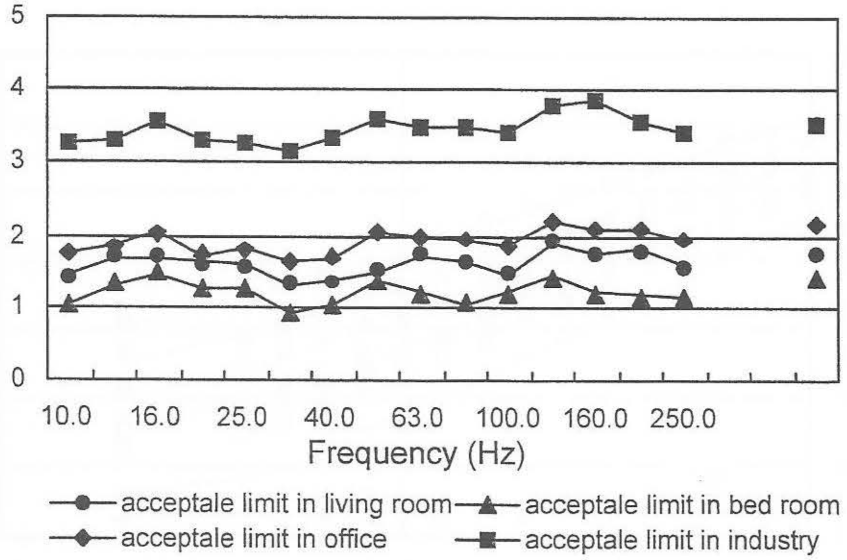

Figure 4: Unpleasantness estimates obtained from sound pressure levels of acceptable limits for different living situations.

Relations between the results of this study and previously obtained results. The results of Figure 2 were compared with the equal loudness contours which were shown in the paper of Lydolf, M. and Møller[3]. The gradients of equal unpleasantness contours were rather gentle than the equal loudness contours below around 50 Hz. This tendency was clearer in lower level unpleasantness and loud ness contours. This means that loudness contours is not enough to evaluate unpleasantness at low frequency noise. However, the difference may not be necessarily resulted from the difference of loudness and unpleasantness, because the gradient of threshold curve was also more gentle and lower in our results. One of the reasons might be the difference of subjects. In our subjects include many housewives who might more sensitive to low frequency noise. For more precise discussion, further experiments will be necessary concerning with sex and age differences of sensitivity to low frequency noise.

Conclusions

1) Acceptable limit levels depended on situations.
2) Acceptable limits of a given situation coincided with particular level of unpleasantness.
3) Equal unpleasantness contours were successfully estimated by a 3rd order polynomials.
4) Gradients of equal unpleasantness contours were slightly milder than equal loudness contours.

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9th International Meeting
17th-19th May, 2000
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Infrasound Pressure Meter and Examples of Measuring Data

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Summary

Recently, complaints about low frequency noise are increasing in Japan. In Inter-Noise '99, Ochiai has reported following three kinds of evaluation methods for effects on caused by infra and low frequency noise.

(1) A evaluation for rattling of doors or windows.
(2) A evaluation for psychological and sleep effects.
(3) A evaluation for oppressive or vibratory sensation.

We have developed a measuring instrument corresponding to above evaluation methods. In this report, an outline of the instrument and examples of infra and low frequency noise data is introduced.

Introduction

In recent years infra and low frequency(ILF) noise problem has been catching lots of attention with increasing number of complaints. More than half of those complaints are in regard to noise or vibration most of which is recognized by rattling of structures caused by ILF noise .The sound pressure level which makes windows or doors rattle has a different characteristic of frequencies from the sound pressure level which a human senses ILF noise. Based on this, Ochiai and his study group have proposed an evaluation method of ILF noise in Inter-noise 99 last year [1]. An instrument in order to measure ILF noise has been recently developed by us based on that idea. In this paper, the features of the meter and the examples of ILF noise measured in the field will be presented.

Evaluation method of ILF noise

The proposed evaluation method [1] of ILF noise is as follows:

The range of frequencies of ILF noise is defined as 1-80 Hz in the central frequency of 1/3 octave band.

The influence caused by ILF noise should be evaluated based on the three following aspects;

(1) The rattling of doors or windows in a house caused by IFL noise.
(2) The psychological effect and disturbance of sleep caused by infrasound;
(3) The oppressive or vibratory sensation caused by low frequency noise.

The evaluation levels of each item above should be as follows

(1) 1/3 octave band sound pressure level (5-50 Hz)
(2) 1/3 octave band sound pressure level (5-80 Hz)
(3) G weighted sound pressure level

Infrasound Level Meter (ISLM)

The ISLM is capable of carrying out an operation of G weighted sound pressure level provided by ISO Standards and 1/3 octave real-time analysis simultaneously.

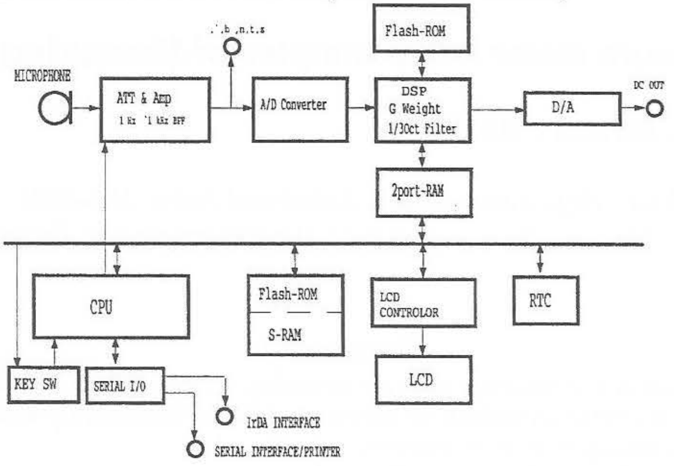


Figure 1. Bock Diagram of Infrasound Sound Pessure Level Meter

The structure of ISLM

The figure 1 shows the block of ISLM. The microphone is made of ceramic which is integrated with a pre-amplifier specialized to measure ILF noise.

The signal appropriately amplified by the analogue amplifier is sent to A/D converter. Output of the A/D converter (16 bit) is processed by DSP operation. This operation is capable of various calculation such as G weighted sound pressure level and 1/3 octave band level. The processed results by DSP are controlled by a microprocessor and transferred to the liquid crystal screen. The results also can be outputted into an external printer or into a personal computer via serial transmission. This ISLM is as small as an ordinary portable sound level meter.

Specifications for Infrasound Level Meter.

Applicable Standards : ISO 7196:1995, JIS C 1513:1983 III type, IEC 61260:1995 Class 1
Measurement Function : Instantaneous sound pressure level, LP. Equivalent Continuous sound pressure level, Leq. Maximum sound pressure level, Lmax.
Wave form peak level, Lpeak
Measurement Time : 10 sec, 1, 5, 10, 15, 30, 60 minutes
Microphone : Ceramic microphone integrated with pre-amplifier
Measurement Level : G weighted, 50 - 147 dB
Time weighting : F (125m / sec), S (1 sec.), 10 sec. Lpeak
Frequency Weighting : G
Frequency Analysis : 1/3 octave band
Capacity of Memory : Manual Storage (200 addr.). Automatic Storage (2000 sddr.)
Trigger Function : On exceeding the pre-set level, operation automatically can be started.
Data Display and interface : Bar graph or level time history on LCD. Serial or Infra-red on Port
Power supply : Four 1.5 V LR-6/AA size alkaline cell or external AC adapter, NC-94
Buttery Life : Approximately 6 hours (when alkaline cell battery used, 25□)
Dimensions and Weight : 319 (L) x 100 (W) x 50 (H) mm, Approx. 900g. (including the battery)

Results from low frequency noise survey

Results from measurement of G-weighted sound pressure level in the living environment

Survey to measure ILF noise was conducted in different sites in the community as well as the periphery of the various source of ILF noise. The survey was carried out at 312 sites; 248 outdoor sites and 64 indoor sites including inside the vehicles. The results were processed based on Lmax observed during the survey. The figure 2 shows a distribution of G-weighted sound pressure levels in the living space. The measured sound pressure levels on average are 70-79 dB in cities, and 76 dB inside a house. These values are approximately 15-30 dB smaller than the threshold which could bother a sense of human which value is 95 to 100 dB. For nearby sites of the source of ILF noise, a highway bridge, a commuter train railroad neighborhood, an airport neighborhood, and a port area were picked up for survey. The measured sound pressure level on average was 92-99 dB. Interesting results were obtained in the vehicles and the area near the source of noise inside the factory building. The average level is 111 dB and 103 dB respectively, which are very high level. The other measured data are: 130 dB in a car driving on the highway with the windows partly open; 119 dB near a dam where the neighbors have been making complaints about the noise when discharging water. Those are the areas where a strong infrasound was sensed when a survey was conducted.

Example of frequency characteristics of ILF noise measured in the living environment.

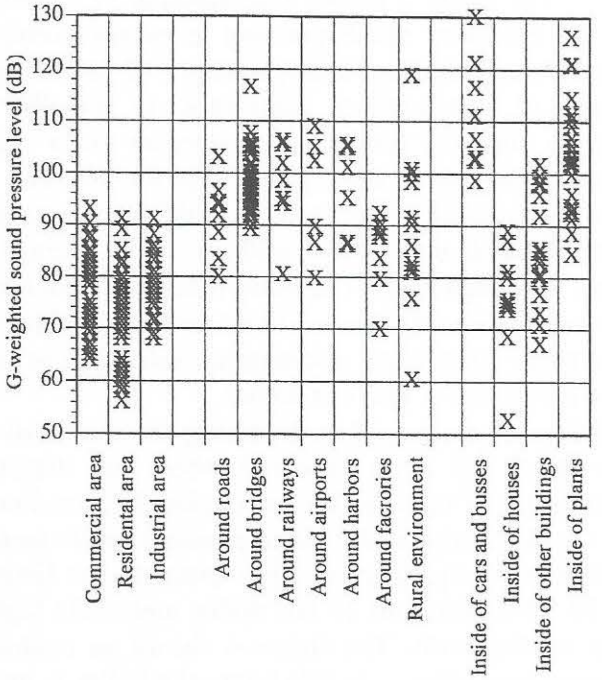
The figure 3 shows an example of spectrum of ILF noise observed where felt discomfort. Comparing the spectrum of ILF noise to the result of laboratory experiments (broken line)[2)] in regard to oppressive or vibratory sensation, it was found that the sound pressure levels measured in the field are higher than the result of laboratory experiments. For example the frequency level inside a bus in a motion is 12.5 Hz - 80 Hz higher, and 25 Hz, 40Hz, and 63Hz higher in case of a passenger side of the cruise ship on the berth. The figure 4 shows an example of spectrum of ILF noise generated from the house use boiler. In this house the boiler is installed inside the building, and doors and windows rattle when the shower in use in a bathroom. Considering the rattling threshold which has already been proved by the experiment in a laboratory, it was confirmed that some range of the IFL noise exceeded the rattling threshold.

Frequency characteristics of ILF noise at the sites where complaints have been made.

In 1995 the Environment Agency carried out a survey in regard to ILF noise on each municipality using the same survey format[4)]. The figures 5 and 6 show the examples of spectrum of ILF noise at the sites where complaints have been made. The figure 5 identifies a complaint sensed psychologically caused by ILF noise generated by a vibrating screen. In this case a standing wave of 31.5 Hz was observed inside the house. Comparing the spectrum of ILF noise to the threshold in regard to the oppressive or vibratory sensation (broken line)[2)], the actual figures are larger than the tested figures. The spectrum after the countermeasure was taken are also shown, which proves that the countermeasure successfully lowered the spectrum of ILF noise to the level of the tested figures in regard to the oppressive or vibratory sensation, and the complaints stopped. In case of the figure 6, a dust chamber makes doors and windows rattle. In this case excessive element of ILF noise is observed in the 8Hz band, which exceeds the threshold of rattling starts (broken line) [3)].

Conclusion

This report describes the specifications of the sound level meter produced based on the evaluation method of ILF noise which was proposed in Japan recently, and introduced the actual data of ILF noise measured by the field. It could be concluded that this Infrasound Level Meter would be a great tool to analyze ILF noise and to clarify influence on human or structures such as doors and windows. Several reviews have reported in regard to measurement and evaluation of ILF noise using G-weighted sound pressure level or 1/3 octave band level from various countries. This Infrasound Level Meter should be capable enough to measure and evaluate the level of ILF noise.



Reference

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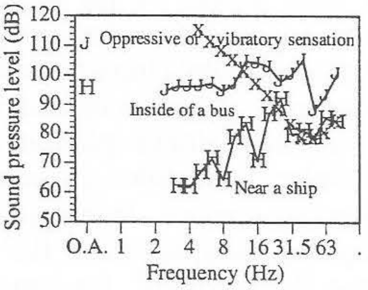
Figure 2 G-weighted sound pressure level of infra and lowfrequency noise in the living environment.



Figere 3 Spectra of ILF noise.

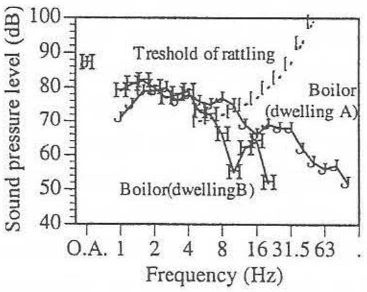


Figure 4 Spectra of ILF noise.

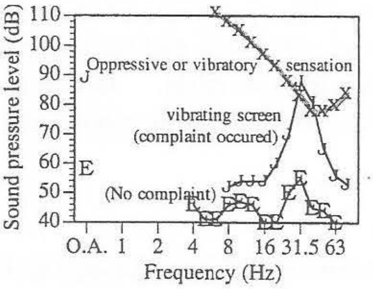


Figure 5 Spectra of ILF noise.

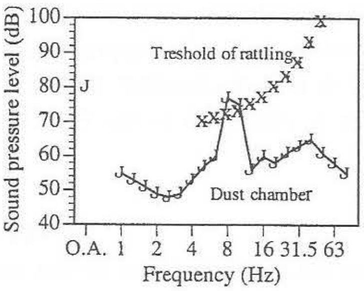


Figure 6 Spectrum of ILF noise.

Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Danish guidelines on environmental low frequency noise, infrasound and vibration

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Summary

In Denmark a set of guidelines for measurement and assessment of environmental low frequency noise, infrasound and vibration was published in 1997 as "Information from the Danish Environmental Protection Agency no. 9/1997" (Miljøstyrelsen[2]). Recommended measurement methods are specified, and recommended limit values for noise and vibration are given. In this paper a brief description of the measurement methods is given, the recommended limit values are shown, and the background for the measurement and assessment methods is discussed.

Introduction

Denmark has had recommended limit values for environmental noise since 1974, when the first guidelines for assessing industrial noise were published. These limits are given in A-weighted levels only, and they do not specifically consider low frequency noise. In the 1984 edition of the guidelines, a warning was given against a direct application of the limit values in cases with low frequency noise, as the annoyance would then be underestimated. However no recommended assessment method for low frequency noise could be given at that time.

When the general knowledge on hearing in the low frequency region had improved, and drafts or suggestions for assessment methods for low frequency noise were published (Piorr and Wietlake[7]; Vercammen[11, 12]), it was considered that there was an adequate background for a recommended assessment method to be published. It was realised that the knowledge on this topic was not complete and that not all questions could be fully answered. But it would be unacceptable if the existing knowledge was not exploited and made accessible to the authorities and the laboratories dealing with problems due to low frequency noise.

Guidelines for the assessment of environmental vibration were published in Denmark in 1983. These guidelines were updated and were published jointly with the guidelines for low frequency noise and infrasound.

Background and assumptions, noise

Infrasound is sound with frequencies lower than 20 Hz. It is well established that infrasound can be heard (or felt) provided it is loud enough, and a hearing threshold can be determined. There is some conformity between the average thresholds found in different investigations in the literature, as is illustrated in Figure 1.

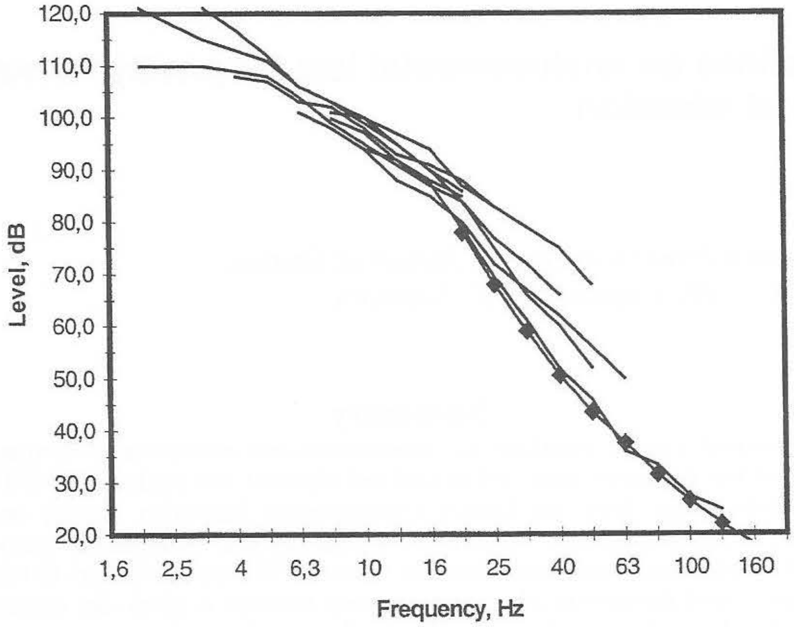

Figure 1. Examples of hearing thresholds. The standardised hearing threshold (ISO 389-7) is shown with diamond symbols.

Also the loudness of infrasound has been investigated (Møller and Andresen[4]). It was found that the loudness increased extremely rapidly with increasing sound level above the hearing threshold. The loudness would increase by 40 Phones from a level increase of only about 10 dB at frequencies 2 and 4 Hz. In Møller[3] it was shown that also the annoyance from audible infrasound increased very rapidly with increasing sound level, and it was found that there is a close relation between the G-weighted level of the infrasound and the annoyance sensation.

It is assumed that infrasound that cannot be heard is not annoying, and it is believed that it has no other adverse or health effects. It is also assumed that infrasound only slightly above the hearing threshold may be annoying. The average hearing threshold for infrasound corresponds to tones each having a G-weighted level of ca. $L_{pG} = 96$ dB.

In the lowest region of the frequency range above 20 Hz, a simple inspection of the standardised equal loudness contours reveal that at the lowest frequencies (20 – 50 Hz) the loudness increases much more with increasing level than at higher frequencies, see Figure 2. When the sound pressure level in this region increases with 20 dB, the loudness increases almost 40 Phones, while this level increase at 1000 Hz will increase the loudness by 20 Phones – by definition. Thus the so-called 'narrowing of the dynamic range' is less than it is in the infrasound region. It would appear that the frequency range 20 – about 150 Hz can be regarded as a transition zone between the infrasound region and the middle frequencies.

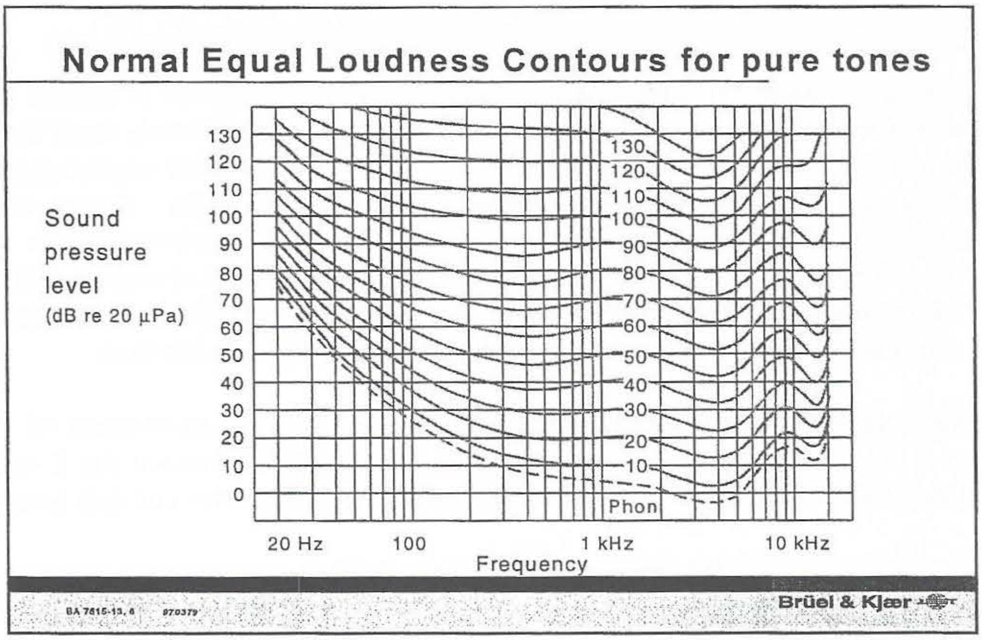

Figure 2. Standardised Equal Loudness Contours from ISO 226. (Reproduced from Brüel & Kjær lecture notes "Psychoacoustics – a qualitative description" BA 7615-13.)

The A-weighting filter was originally defined as a 'best fit' to the shape of the equal loudness contours at low levels. A closer inspection reveals that the A-weighting filter overestimates the loudness at low levels at the lowest frequencies. This is also true for the proposed revision of equal loudness contours (Møller and Lydolf[5]). Thus it can be expected that the use of the A-weighting corrections specifically in the low frequency region would be advantageous in giving a more strict assessment at the lowest frequencies in this region.

This does not imply that the A-weighted noise level (of the entire frequency range) in itself will give a good measure of the loudness or even the annoyance of noise with a low frequency content. On the contrary it is a frequent observation that the A-weighted noise level underestimates the annoyance of low frequency noise, which may possibly be caused by the above mentioned 'narrowing of the dynamic range'.

Most of the measurements of the hearing threshold and other investigations on hearing in the low frequency region are made with single tones or narrowband noise. There is no established method for evaluating broadband low frequency noise or low frequency noise consisting of several tones. It can be taken as a secure assumption that the concept of loudness summation within a critical band also is valid at low frequencies and in the infrasound range, and that the entire frequency region from ca. 1 Hz to approx. 150 Hz can be regarded as one critical band.

An assessment method based on this concept would call for a sound level dependent weighting function in the entire region that will consider the extreme steepness of the loudness vs. noise level dependence in the infrasound range. Neither generally accepted weighting functions nor the level dependent filters exist, so a simpler procedure will have to be followed.

It is natural to use the standardised G-weighting function (ISO 7196) for an assessment of infrasound. The G-weighting however has a sharp cut-off at 20 Hz and is not intended for use at higher frequencies. This feature may result in an underestimation of loudness at frequencies between ca. 16 and 20 Hz. The A-weighting function may be used to assess the noise in the low frequency range up to about 150 Hz. It is necessary to limit the frequency range by a low-pass filter to avoid a mixed evaluation of low frequency noise and noise at middle frequencies. The low frequency noise is assessed by use of a set of criteria separately from the criteria used with the overall A-weighted noise level. To overcome the possible underestimation of the frequency range 16 – 20 Hz, the A-weighting is used down to 10 Hz. Due to the excessive tolerances at low frequencies on the A-weighting filter in the instrumentation standard (IEC 651), the A-weighted level of the low frequency noise cannot be measured with a usual sound level meter supplied with a low pass filter. The level in stead must be synthesised from a narrowband frequency analysis by addition of the nominal weighting function.

It is sometimes suggested to use the C-weighted noise level for an assessment of low frequency noise. This is not encouraged, as there is a poor relation between the C-weighting function and the shape of the equal-loudness contours at low frequencies and low levels

Recommended noise limits

An environmentally acceptable infrasound level must be below the hearing threshold. It can be assumed that the individual hearing threshold may be 10 dB lower than the average threshold, so the recommended limit for environmental infrasound must be L_{pG} = 85 dB.

For the low frequency noise the A-weighted level of the noise in the frequency range 10 – 160 Hz is regarded, the symbol used is $L_{pA,LF}$. The recommended limits are 5 – 15 dB lower than the ordinary noise limits, and the lowest recommended limit $L_{pA,LF}$ = 20 dB has a close connection with the infrasound limit L_{pG} = 85 dB as illustrated in Figure 3.

	Infrasound, L_{pG}	Low frequency noise, $L_{pA,LF}$	Usual noise limit, L_{pA}
Dwelling, evening & night	85 dB	20 dB	30 dB / 25 dB
Dwelling, day	85 dB	25 dB	30 dB (day & evening)
Classroom, office etc.	85 dB	30 dB	40 dB
Other room in enterprises	90 dB	35 dB	50 dB

Table 1. Recommended limits for infrasound (L_{pG}), for low frequency noise ($L_{pA,LF}$), and the usual noise limit for noise from enterprises (L_{pA} , used when the enterprise and the dwelling is in the same building). All levels in dB re 20 μPa.

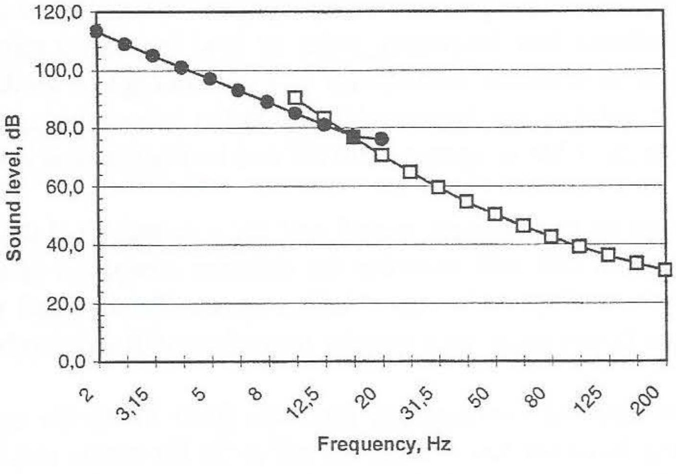

Figure 3. Curves showing the sound levels of tones each giving an infrasound level of L_{pG} = 85 dB or an A-weighted level of L_{pA} = 20 dB, both levels re 20 μPa.

The noise limits are compared to the sound levels measured over a reference time period of 10 minutes; the usual noise limits in force are however used with reference time periods of 8 hours, 1 hour and ½ hour for the day, the evening, and the night period respectively. If the noise is impulsive, e.g. from single blows with a press or a forging hammer, the recommended limits are reduced by 5 dB.

Noise measuring method

Normally measurement of environmental noise takes place outdoors. This is not possible with low frequency noise partly due to the disturbance from even light wind, partly because an outdoor measurement will not consider re-radiated structure borne noise. Furthermore it is a frequent observation that low frequency noise is considered more annoying indoors.

The recommended noise measurement method was adapted from a recent Swedish measurement method (SP[9]) to fulfil the following demands:

- it shall give precise and reproducible results, enabling i.a. a meaningful control measurement after noise abatement has been made,
- it shall give reliable and representative results that represents typical high sound levels experienced by the occupants,
- it shall be simple and feasible for the noise laboratories using normal sound measurement equipment, so that it will be used in practice and the costs will not be excessive.

When the noise level is measured in only one position in a room, there is a vast uncertainty on the result because the noise level differs considerably from one point to another. With tonal noise this is very pronounced due to standing waves, giving a pattern of narrow very deep minima of the noise level. Differences above 30 dB are seen in practise. In general a "characteristic point" in a dwelling where a representative noise measurement can be made sufficiently precise cannot be defined. It has been suggested to measure the noise level in a corner, as the noise level is often higher here than in other points in the room. This generally holds well for higher frequencies, but investigations have shown that the infrasound level can be as much as 10 dB lower in a corner than in other points in the room.

The measurement method specifies that the noise normally shall be measured in at least 3 points in each room. One point is chosen near a corner, 0.5 – 1 m from the adjoining walls and 1 – 1.5 m above the floor. The other points are chosen so they represent normal staying in the room, at least 0.5 m from walls and large pieces of furniture and 1 – 1.5 m above the floor. Often the occupants can identify points where the noise is highest, and it is important to measure in these points. If they cannot, the technician must choose measuring points according to his own judgement; however points near the midpoint of the room shall be avoided as the noise level often is lowest here. In small rooms (less than ca. 20 m^2, the noise can be measured in two points in different corners 0.5 – 1 m from the adjoining walls and 1 – 1.5 m above the floor.

The noise is measured in the room in the dwelling where the occupants states that the noise is highest; supplementary measurements can be made in other rooms (sleeping room or living room).

The operating conditions of the noise source shall be representative for the situation that is complained about, and the background noise shall be as low as possible. Windows and doors shall be closed; if it is claimed that the low frequency noise is stronger with open windows a supplementary measurement can then be made. If possible the background noise is measured with the noise source stopped. This also identifies which source is responsible for which part of the noise.

Narrowband analysis are made of the noise from each measurement point. Normally the noise levels will have to be averaged over at least 5 minutes to average out random fluctuations due to sound propagation. If the noise source is varying, the analysis interval shall equal the reference time interval of 10 minutes. When it has been possible to measure the background noise, the spectra are corrected for background noise. The measured (and corrected) spectra are added to the nominal G- and A-weighting corrections. By summation the infrasound level (of the noise in the frequency range from 2 – 5 Hz up to 20 Hz, usually the frequency components below ca. 5 Hz has no influence on the G-weighted level) and the A-weighted level of the noise in the range 10 – 160 Hz is calculated. The energy average of the G- and the A-weighted noise level from all the measurement points in the same room is calculated and is compared to the recommended noise limits.

Background and assumptions, vibration

Vibrations in the environment are usually considered annoying at a level that is only slightly above the sensation threshold. This assumption has been the basis for the Danish guidelines on vibration since 1983. The vibration level is measured as a broadband level that is weighted with a well defined function. For vibration the standardised "whole body combined" weighting is used, also called "KB-weighting". This weighting is a simple low-pass filtering of the acceleration signal below 5.7 Hz; in addition a frequency limiting to the range 1 – 80 Hz is prescribed. Vibrations are measured on the floor. The maximum level is used as a basis for the assessment. For stationary vibration sources there is no difference between the maximum and the average level, however most of the experience in this topic concerns vibration from railways or from construction activities.

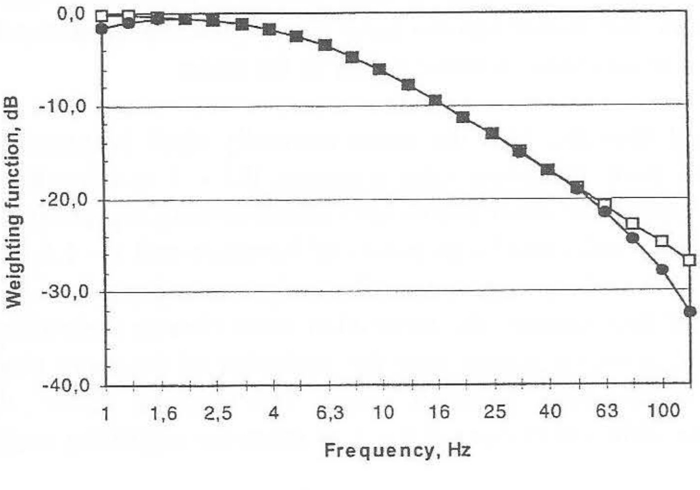

Figure 4. Whole-body combined weighting function shown both with and without band limiting to 1 – 80 Hz.

In 1991 a Nordtest[6] method was published, based on the experience with i.a. the Danish guidelines. This method gives measurements with better accuracy in specifying more measurement points. Also the international standardisation on this topic has moved; at present the draft for a revised ISO 2631-2 "Vibration in buildings (1 – 80 Hz)" is on vote.

When setting limits that reflects environmentally acceptable vibration levels, only the tactile vibration is considered. Re-radiated noise that often accompanies vibration is assessed as low frequency noise. Secondary phenomena such as rattling windows or pieces of furniture are not considered. Questions of possible building damage that often worry occupants are not taken account when setting the recommended limit values. It should be noted that the criteria traditionally used for assessment of possible damage are much higher than the 'comfort criteria'.

Measurement and assessment of vibration

Vibrations are measured in the room where the occupants experience them to be strongest. According to his judgement the technician can measure in other rooms too. Measurements are made in that point and that direction where the highest level is expected. With typical Danish buildings this is the vertical direction, and in buildings with two or more storeys the level usually is higher on the upper storey. The highest level is expected on the midpoint of the floor with the longest free span. Supplementary measurements are made in 1 – 2 points at least 1 m from the primary measurement point and from the walls. The transducer (accelerometer) shall have firm contact with the floor. If the floor is carpeted, a probe that penetrates the carpet can be used for measurement of vertical vibration. On lightweight (floating) floors the measured level depends on the loading of the floor. For that reason the floor should be loaded by a person that sits quietly on a chair near by the measurement point. The use of weights is not encouraged.

The signal from the transducer is frequency weighted, and the time dependent weighted acceleration level is recorded. Time weighting constant S (slow) is used; as a close approximation a running RMS with integration interval 2 s can also be used (this is specified in the recent draft for ISO 2631-2). The energy average of the maximum levels that occur simultaneously in the (2 or more) measuring points is calculated and is compared to the recommended vibration limits (Table 2).

	Weighted acceleration level, L_{aw}	Weighted acceleration a_w	Corresponding weighted velocity v_w
Dwelling in dwelling areas (day and night) or in mixed areas (evening & night), institution	75 dB	5.6 mm/s^2	0.16 mm/s
Dwelling in mixed areas (day), office and classroom	80 dB	10 mm/s^2	0.3 mm/s
Other room in enterprises	85 dB	17.8 mm/s^2	0.5 mm/s

Table 2. Recommended limits for vibration, given both as the weighted acceleration level in dB re 10^{-6} m/s^2, weighted vibration (mm/s$^{2)}$, and the corresponding weighted velocity (mm/s)

For comparison with the recommended vibration limits it can be mentioned that the threshold of sensation is about 72 dB (re 10^{-6} m/s^2) or 4 mm/s^2.

Comparison to other guidelines

Procedures and guidelines for assessment of environmental low frequency noise have recently been published in i.a. Sweden, Germany, and The Netherlands (Socialstyrelsen[8], DIN[1], Stichting Geluidhinder[10]). It is relevant to compare the Danish recommended assessment method with these methods, although this is difficult to do precisely because the assessment methods and the corresponding measurement methods differ.

The German standardised method distinguishes between tonal noise and broadband noise. For broadband noise the recommended limits are 25 dB at night and 35 dB at day (A-weighted levels in the frequency range 10 – 80 Hz). For tonal noise the tone level must not exceed a 'threshold' that corresponds to an A-weighted level of between 25 dB (at 20 Hz) and 6 dB (at 80 Hz). At 80 Hz however an exceeding of up to 5 dB is allowed. The Swedish and the Dutch assessment methods also specify a 'threshold' that must not be exceeded. The Swedish method deals with the range 31.5 – 200 Hz, while the Dutch concentrates on 20 – 100 Hz. The Dutch 'threshold' corresponds closely to the German, but no relaxation is allowed at higher frequencies. The Swedish threshold corresponds to the German threshold at the lowest frequencies, and to an A-weighted level of ca. 20 dB at frequencies above ca. 100 Hz.

If the low frequency noise consists of one tone only, the Danish assessment method is the most strict at frequencies below 25 Hz. In the interval 40 – 50 Hz the other methods roughly give the same assessment, which is some dB stricter than the Danish. At higher frequencies the German and the Dutch method deviate and give significantly stricter assessment than both the Danish and the Swedish methods. If the noise consists of more tones or broadband noise, the Danish assessment method will take the possible loudness summation into account and assess this stricter, while the tree other methods only consider the 'loudest' of the narrowband levels.

A comparison of recommended vibration limits has recently been made within the framework of revision of ISO 2631-2. A questionnaire was made where the countries should indicate their 'guidance values above which adverse comments due to building vibration could occur'. Even if such a comparison must be regarded with precaution, as many important parameters are not considered, some guidance can be taken from it. It was found that the Danish recommended vibration limits were among the lowest.

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and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Ergonomics & Vibration in Powered Hand Tools Used in Meat Processing

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Summary

The purpose of this study was to determine the triaxial acceleration levels of a group of powered circular knives extensively used in the meat processing industry. These tools were tested in real time under actual work conditions while the operators used the tools in 23 different applications. The length of the study was 11 months, encompassing 685 tools, at 13 plant sites using 5 different diameters of circular tools. All vibration tool measurements were recorded from three triaxially mounted, individually calibrated, PCB accelerometers. Customized software programs allowed a Gateway 2000 SOLO computer to cycle, collect, and record vibration data for a minimum of a one minute time frame. The study results showed that neither the ANSI S3.34 nor the ACGIH hand-arm vibration standards were exceeded for an 8-hour workday. The median acceleration levels for the five different sized diameter tools did not significantly differ. The operating levels increased only slightly from a new tool that has been determined to be operating at maximum efficiency. Examining the different tool applications, operators, plant locations and tool conditions resulted in concluding that for this type of tool the most important factor contributing to the acceleration intensity levels was tool maintenance and conditions of its parts. Tools with higher vibration acceleration levels were disassembled and found to have at least one part severely worn or damaged. After the part(s) were replaced, the tool was re-tested under the same work conditions, the vibration acceleration levels on average decreased 16%. As part of an overall effort, operator exposure to vibration generated by these powered circular knives can be significantly reduced and controlled by proper tool care and maintenance.

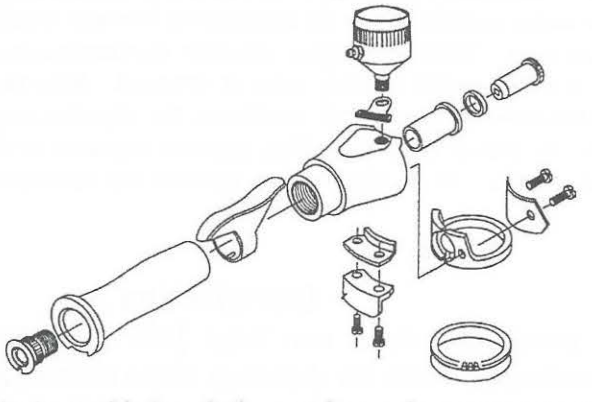
Introduction

Meat processing plants and their associated jobs are labor intensive and require the manipulation of hand tools. Since the depiction of the meat industry in 1904[1], automation has allowed the processing speeds to significantly increase. Current production line speeds range from 200-400 cattle per hour and 800-1200 hogs per hour. Each animal carcass (unit) processed is unique and therefore all operations by line workers require different degrees of body movements to accomplish each task, added to the shear speed of the production line. This high repetition, force, body angles, taxing of workers' bodies and other contributing factors such as cold working temperatures, power tool vibration, carcass weight have all contributed to increasing rates of Cumulative Trauma Disorders (CTD) and associated problems in the meat industry.

One situation that the meat industry has faced since early man is the removal of as much meat as possible from each animal carcass. This had not been a problem for early man in all civilizations until the agrarian society became urban and quickly grew. With urbanization the demand for high volume meat processing plants developed; sometimes at the expense of the local butcher shop. Currently in the high volume meat processing industry, various types of powered hand tools have been developed to address high consumer demand for processed meat products. These tools are powered by compressed air, electric, and hydraulic sources and are used to: remove animal hides from the carcass; splitting bones and joints; removing meat from bones (de-boning) and trimming fat from the meat. This orchestra of power tools, automated machinery, and manual straight knives provide a background for the current high volume processing of meat.

In 1954, an innovative, single hand operated electrical powered tool, circular knife was developed to efficiently remove meat from bones and trim fat from meat[2]. This power tool design is diagrammatically shown in Figure 1. This power tool was one solution to the use of a manual straight knife in both the slaughtering and further processing areas. In the slaughtering areas these powered circular knives are used to remove: stick wounds, contaminated meat, and eyelids from the animal carcass. In the processing floor these knives are used for bone removal, removal of meat from bone, trimming fat, and the shaping of primal muscles. Over the years this powered circular knife has been accepted by the industry and thousands are in use worldwide by numerous meat processors. In operation, the circular knife is electrically powered by an AC motor whose output motion is mechanically transferred through a long flexible shaft into a pinion gear, which changes the rotational motion of the motor to the teeth of the pinion gear, thus moving a sharp, circular blade confined within a housing, see Figure 1. A pneumatic powered circular knife is also used; eliminating the need for the flexible shaft. Blade diameters vary, as do their housings. Different angles of blade surfaces are also presented.

FIGURE 1. Powered circular knife used in meat processing



This powered hand tool design with its plethora of uses in meat processing presents different and significant challenges from both an ergonomic and vibration acceleration standpoints.

Background

A 1988 study[3] evaluated the design of this circular knife and examined its ergonomic and vibration features and tool maintenance history. This study showed strong relationships between this power tool's design (weight, center of gravity, torque, handle sizes/contour/material, blade sharpness) and vibration acceleration levels and the maintenance received. In a 1993 ergonomics report[4] prepared for a major meat processing company, this circular knife was assessed as a "medium-low" risk job using a five category risk scale: low, medium-low, medium, medium-high, and high risk jobs. Risk factors identified in this ergonomic report included: repetitive hand motions, wrist deviations, continuous standing, bent neck position, and static grip force of the non-dominant hand. Finally, another study[5] evaluated ergonomic solutions to problems in the poultry industry stated that automation is limited due to the variation among animals and that "Powered circular blade trimmers and scissors are commercially available to trim turkey meat. Such tools can help in reducing the repetitive nature of cuts and the amount of force required to trim meat products. Cutting tools can decrease the amount of force needed to trim or de-bone if they are maintained sharp. Manual and powered cutting tools only work as well as they are maintained. Power tools that are not maintained lose their ergonomic value of reducing force and repetitions when they generate excess vibration".

Because of the foregoing and the fact that in the U.S. alone there are some 2 million workers regularly exposed to power tool vibration[6] in numerous diverse industries such as metal and wood working, mining, construction, etc., we believe there is a need to *proactively* protect workers from the effects of hand-arm vibration exposure, known as Hand-Arm Vibration Syndrome[7] and related musculoskeletal disorders (MSD). Thus the rationale and purpose of this extensive study, a *first* in the meat industry, was to *proactively* determine the relationships between this circular electric powered knife design/type/maintenance versus triaxial rms vibration acceleration levels emanating from these tools as used under actual working conditions in various U.S. meat processing plants using a variety of experienced production line workers as test subjects.

Ergonomic & Hand-ArmVibration Standards & Guides

As a practical matter there are a limited number of guidelines one can refer to when designing *both* an ergonomic *and* anti-vibration (A/V) powered hand tool as a single product[7, 8]. Ergonomic guidelines[9] were first published in 1990 to address the increasing rate of CTD's in the meat industry. These guidelines addressed the ergonomic considerations for powered hand tools including weight, handle characteristics, tool vibration and job requirements. Also, other proposed standards such as the ANSI Z365-DRAFT[10] standard on reducing upper extremity CTD's attempts to elaborate on some of the recommendations in the Meatpackers Guidelines.

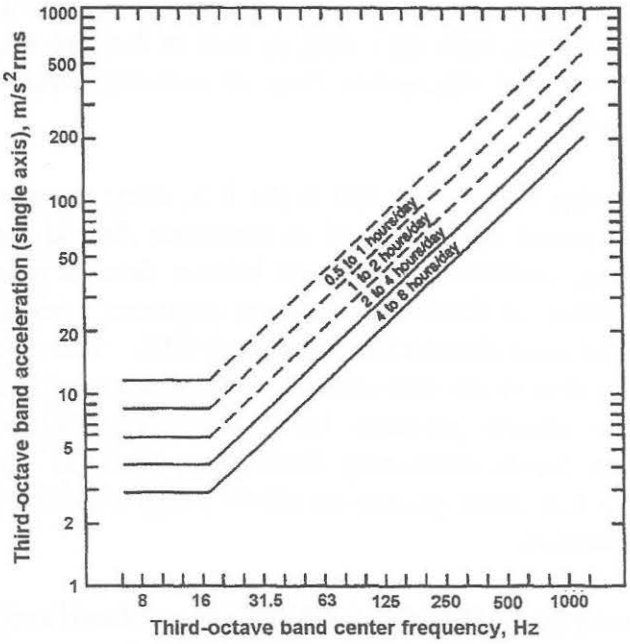
There are potentially several applicable Hand-Arm Vibration (HAV) standards/guides that can be used to evaluate the circular powered knife design. Internationally, there is ISO 5349 [11] and ISO 8662 [12] and in the U.S. there is the NIOSH, HAV standard [13] #89-106, ANSI S3.34 [14], and ACGIH, HAV standard [15]; each of which will be briefly discussed for this application:

- ISO 5349, first promulgated in 1986, can be used for many different tools but lacks any recommendations or limits with regard to *daily tool use*, instead this document defers to each country to establish their own daily HAV limits. Thus this standard was *not* used in our study.
- ISO 8662, the first parts of which were promulgated in 1988, is a multi-part tool-specific process standard which does *not* address the circular knife. Further, ISO 8662-1 clearly

states its intended use was not to assess human response to HAV, rather it is an attempt to improve tool measurement techniques in certain other tool types such as grinders, chipping hammers, etc. In doing so, however, the recommended procedures usually limit the tool axes from the customary three (triaxial) to as few as one axis with vibration measurements obtained not from the actual work environment, rather special tool jigs are used instead. Thus this standard was *not* used for our study.

- NIOSH #89-106, was first promulgated in 1989, and does *not* contain nor recommend *any* HAV daily or other exposure limits; rather it recommends a series of administrative measures for reducing workplace HAV. Thus this standard was *not* used for our study.
- ANSI S3.34, was first promulgated in 1986, and *does* recommend, triaxial, weighted, daily HAV exposure limits, graphically shown in Figure 2 as exposure "zones". Thus this standard *was* used in this study.

FIGURE 2. ANSI S3.34, Hand-arm vibration standard daily exposure curves



- ACGIH, HAV standard, was first promulgated in 1984, and *does* recommend, triaxial, weighted, daily HAV exposure limits, numerically shown in Table I. Thus this standard *was* used in this study.

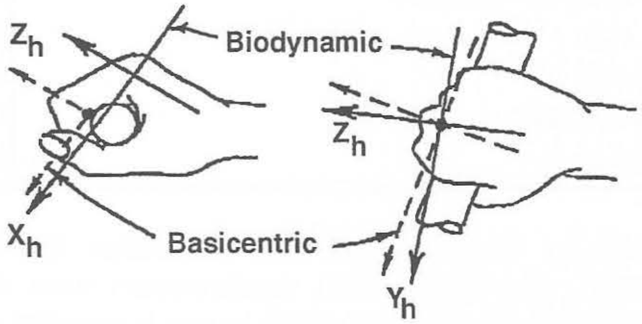
TABLE I. ACGIH-TLV for Hand-Arm Vibration

Total Daily Exposure Duration *	Values of the Dominant, ** Frequency-Weighted, rms, Component Acceleration Which Shall Not Be Exceeded a_K, (a_{Keq})	
	m/s^2	g
4 hours and less than 8	4	0.4
2 hours and less than 4	6	0.61
1 hour and less than 2	8	0.81
Less than 1 hour	12	1.22

*The total time vibration enters the hand per day, whether continuously or intermittently.
**Usually one axis of vibration is dominant over the remaining two axis.
If one or more vibration axis exceeds the Total Daily Exposure then the TLV Has been exceeded.

Finally, for *both* ANSI S3.34 and the ACGIH HAV standards: The measure of linear vibration "intensity" is root-mean-squared (rms) acceleration, obtained triaxially, using the same basicentric coordinate measurement system shown in Figure 3. The same "weighted" 1/3 octave band Fourier vibration spectrum analysis is required for each vibration axis to properly evaluate the triaxial vibration data as applied to both these standards[16].

FIGURE 3. Hand-arm vibration basicentric coordinate system



Methods

Equipment, Data Acquisition & Analysis. When designing this study it became apparent that there was a need to modify both commercially available off-the-shelf vibration equipment and to develop computer software necessary to process the vibration data. Figure 4, diagrammatically shows the equipment setup used in this study; Table II lists the basic (unmodified) equipment used.

FIGURE 4. Flow diagram of study vibration data acquisition system

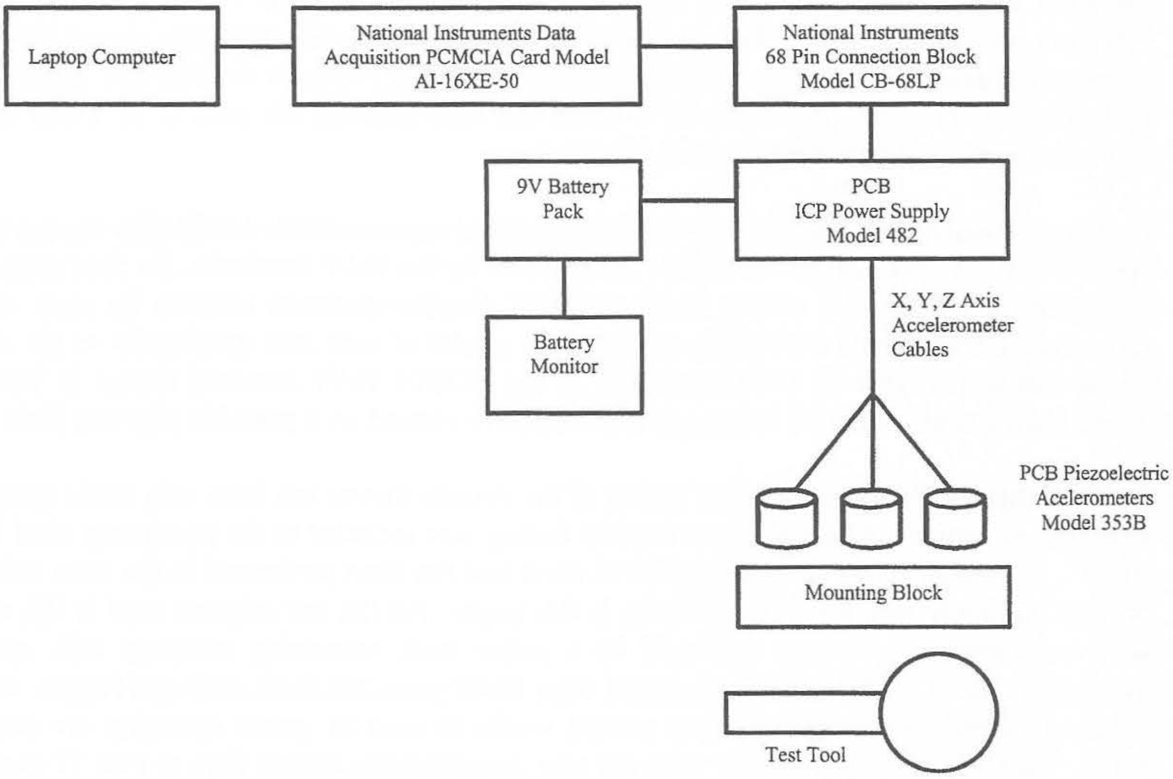


TABLE II. List of Equipment used in study

Equipment	Model
486 Laptop Computer	Gateway Solo
National Instruments Data Acquisition PCMCIA Card	A1-16XE-50
National Instruments 68 Pin Connection Block	CB-68LP
PCB ICP Power Supply	482
PCB Piezoelectric Accelerometers	353B
9V Battery Pack	Generic
Battery Monitor	Generic
Accelerometer Cables	Generic
Mounting Block	Generic

In order to measure the linear rms vibration acceleration impinging on the hand, three lightweight, calibrated, piezoelectric PCB accelerometers were rigidly mounted mutually perpendicular to a small aluminum block which in turn is mounted on the circular knife. The aluminum block has a base that can be mounted on the head of the circular knife, close to the palmer surface of the hand that grips the tool. The acceleration output was electronically conditioned (converting electrical charge to corresponding voltage) and provided needed voltage amplification suitable for analog-to-digital (A/D) conversion, storage, and subsequent Fourier spectrum data processing.

The hardware package is a modified version of National Instruments' Third Octave Analyzer data processing equipment and Labview modified software. This analyzer was customized to acquire (sample) acceleration values every 80 microseconds, multiplexed across all three *x, y, z* vibration axes data channels, for a *minimum* data collection time of 1 minute of continuous vibration acceleration data. This multiplexed sampling data collection rate across the three acceleration data channels is much faster than the minimum [Nyquist criteria] rate required for the vibration standards bandwidth of 5-1,500 Hz; thus insuring for each *x, y, z* axis signal channel, excellent signal integrity, without data loss.

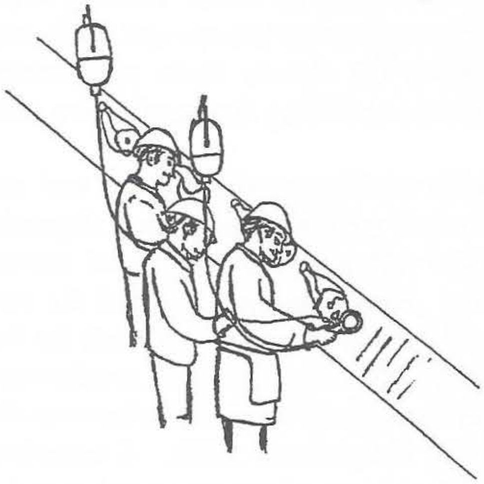
Each *x, y, z* analog data channel was next digitized and converted into ASCII files using a high-speed PCMCIA data acquisition board. As required by the HAV standards, the final steps was to perform a separate 1/3 octave band, weighted, Fourier spectrum analysis for *each* of the three axes vibration data and finally compare the results of each axis graphically to the ANSI S3.34 standard (Figure 2) and numerically to the ACGIH HAV standard shown in Table I. These results could either be hard copy printed and/or viewed on a portable Gateway Solo PC.

Study Subjects. Previous vibration testing of the circular knives has been only static testing in a laboratory setting. Although some in-plant testing was included in the previously cited 1988 study[3], no extensive testing of any powered hand tool has been performed in the meat industry prior to this study which we are reporting in this paper. All the test subjects used in this study were volunteer line workers employed by a major meat processing company with various locations in the U.S. Subjects' ages ranged from 18-65 years old, both male and female, with a range of on-the-job experience from several weeks to over 20 years operating the circular knife. The tools used in this study were not new, ranging from several days to over 11 years of actual use. Prior to testing, all tools were initially assessed as to their physical condition and initial vibration acceleration levels. Other variables considered were tool model (diameter and condition of the blade), type of application used on the production line, and tool maintenance history (condition of the tool).

Testing & Work Environment. All testing was performed on actual meat processing production lines, during normal working hours, with the powered circular knife used in a normal manner by workers who normally use the circular knife as part of their jobs. So as not to interrupt the fast moving meat production line flow and simultaneously accomplish the task of measuring vibration on the circular knife, the triaxial accelerometer mounting block had to be designed to mount/dismount quickly to/from the circular knives. There were other severe physical working conditions of meat processing which had to be addressed in order to conduct this unique study, namely:

- The environmental temperature on processing floors average 7.2° C and over 32.2° C in the slaughtering areas.
- There is significant moisture present in all areas of meat processing.
- In operation, the circular knives are usually covered with fatty tissue, blood, and dried proteins.
- Plant layouts provide only 3 feet of working space per line worker.
- One investigator (securing the accelerometers to the circular knives) had to safely work behind each line worker, during each data gathering run, without interfering in any way with the fast moving production line and/or the line worker(s) using these power tools (Figure 8).
- Workers in meat processing plants are subjected to added hazards of finger and hand: cuts, burns, crushes, punctures, and even amputations. Thus personal protective equipment is used to minimize these hazards using cut resistant gloves and sleeves, plastic arm guards and stainless steel mesh gloves. Also, latex gloves must be used by workers to protect the raw meat from contamination. All of the foregoing, while trying to protect the worker simultaneously reduces their dexterity, tactile response, and restricts necessary movement.

FIGURE 8: Diagram of meat production line with investigator behind line worker



Conducting the Study. Power tool data was gathered over an 11 month period, from 13 U.S. meat processing plants, using 685 circular knives, operated by 630 male and female workers doing the work listed in Table III.

TABLE III. Circular Knife Used in Meat Processing

Tool Diameter (centimeters)	Application (tasks in meat industry)
2.858	Remove bones from loins Trim beef heads Remove liver spots
5.080	Remove meat from neck bones Remove meat from heads Remove tails from hams Remove rib diaphragm meat Remove stick wounds
6.350	Remove cartilage from snout Remove pate meat
7.620	Remove blood clots from jowls De-fat ham muscle seams De-fat loin ends Remove contamination from carcass Remove cheek meat Remove fat from rib cage
12.700	Remove fat from hams Remove fat from loins Remove lean meat from bellies Remove lean meat from back fat Remove skin from bellies Remove skin from shoulders Trim beef rounds

Two investigators conducted this study, one operating the vibration measuring equipment, the other standing directly behind a line worker. In practice, the line worker gave latter investigator a non-running knife, which was then quickly affixed with a triaxial accelerometer-mounting block, secured with two plastic ties at six pounds of force using a tie gun. Once the block was secured, the worker was handed the powered knife and began to perform the task without the customary step of steeling the blade. Steeling is the process of using a smooth or serrated steel rod to realign/straighten the microscopic teeth, which comprise the edge of these blades. Placing a rod against the circular blade edge could potentially interfere with the performance of the tool, therefore, steeling during vibration data collection was not allowed.

During this study the worker would generally take the tool and begin operating the powered knife. Movement of the knife in relation to the product depended on the model, blade size, and application. De-fatting tasks normally would be lateral movement of the forearm across the breath of the worker's body. Removing meat required the worker to push the moving blade downward, horizontal to the body, and then pull towards the body. These fast and continuous hand movements in relation to the task required the accelerometer block be robust and tightly secured to the tool, thus eliminating any interference between the measuring equipment and the worker's activity while using the powered knife. A complete vibration data collection run lasted a minimum of one full minute, whereupon another tool was handed to the worker and the work cycle was repeated. Hand signals were used by the two researchers to begin/end each tool test.

Vibration Data Processing. Computer processing of the numerous electrically powered circular knives' triaxial acceleration data in this study used *both* the ANSI S3.34 HAV standard *and* the ACGIH-HAV standard [known as Threshold Limit Values or TLV] evaluation criteria. In keeping with these standards, for each tested tool, the following data processing procedures[7, 14-16] were used: For each channel of the DAT tape recorded "time domain" vibration data, a separate1/3 octave band, weighted Fourier vibration spectrum was calculated thus converting time domain data into corresponding "frequency domain" spectrum. Three such spectra were calculated, one each for the *x, y, z* axes.

- For *each* such spectrum, a numerical value was calculated in rms acceleration [either in meters/sec/sec or gravitational "g" units, where 1g = 9.81 m/sec/sec]. This value represents the vibration acceleration intensity impinging on the worker's hands in that given direction/axis.
- For each tool, there were three such calculated numerical values, one for the *x* axis, one for the *y* axis, one for the *z* axis. In turn, each of these numerical values was compared to the ACGIH HAV standard given in Table I. For evaluation purposes, if for example, one or more of these three values exceed 4 m/sec/sec [or 0.40 g] then that tool could not be safely operated from 4-8 hours/day; it possibly can be operated for a shorter daily period, depending on the magnitude of each calculated value.
- ANSI S3.34 is a graphical standard wherein for each tested tool, each of the three respective spectra were separately mathematically compared/overlaid over the weighting function graph shown in Figure 2. This standard has been exceeded if one or more spectral lines/peaks, in any one or more of the three spectra, touch or pierce through the weighting function shown as a series of exposure-time-dependent parallel "elbow shaped" curves. Conversely, this standard has not been exceeded if all spectral peaks lie *below* the 4-8 hours/day weighted exposure zone curves.

Results

The results of our vibration tool testing indicated the following:

a) No tool tested exceeded either the ANSI S3.34 standard nor the ACGIH standard for HAV in the critical 4-8 hrs/day usage ranges.

b) Referring to Table IV, the *overall mean* weighted rms acceleration values among the five diameter blade tools [2.858 cm, 5.080 cm, 6.350 cm, 7.620 cm, 12.700 cm] circular knives tested were evenly distributed and varied little, despite the fact that the individual [min.-max. range] weighted acceleration values for each [blade diameter] tool type varied; sometimes considerably.

TABLE IV. Statistical tabulation describing overall mean weighted rms acceleration

Acceleration	**Tool Diameters(centimeters)**				
(m/s^2)	**2.858**	**5.080**	**6.350**	**7.620**	**12.700**
Minimum	1.001	1.001	1.069	1.002	1.002
Median	2.076	1.658	1.630	1.804	1.531
Maximum	2.299	22.315	8.326	7.800	10.209
Std. Dev.	0.426	3.895	1.396	1.279	1.004

We believe the reasons for this wide min.-max. ranges among tool diameter categories is due to one or more of the following tool characteristics:

- The smaller (2.858 cm diameter) tool has a rigid housing or channel in which the blade is captured and guided as it moves. The larger diameter blades with larger housings are only partially captured by a crescent-shaped shoe configuration.
- Adjustability is better with the larger diameter tools, allowing the worker to tighten the "shoe" [or viewable area] of the moving blade and simultaneously minimize the vibration.

- There are design differences in the ability of the product to move out of the path of the moving/rotating blade. The smaller diameter tools are primarily used to remove meat from bones and other sinuous tissues whereas the larger diameter knives are used primarily for fat trimming and removing lean meat from fat. Thus there is less contact with hard [bony] objects when using the larger bladed tools and the product composition [i.e. fat] provides natural blade lubrication.

c) Regarding tool care and maintenance, not unexpectedly, the results indicated that acceleration levels rise with poorly maintained tools. The physical condition of each circular knife was documented before and after testing. We note that when these knives were evaluated as a complete unit as a motor, flexible shaft and casing, handle piece, each element added to the recorded acceleration value. For example, when a motor was incorrectly positioned ergonomically too low in relation to the working surface, the acceleration level of flexible shaft, which couples the motor motion to the tool, increased. Poorly maintained flexible shafts, worn parts, and lack of tool lubrication all contributed to the higher measured acceleration values.

Discussion

The tested circular cutting knives used in the meat processing industry showed acceleration levels less than the 8 hour/day limit of both ANSI S3.34 & the ACGIH HAV standard if they were properly maintained. Not unsurprisingly, worn tool parts or poorly maintained tools resulted in higher vibration acceleration levels; these tools when examined clearly showed excessive wear and/or damage to one or more parts such as blades, housings, pinion gears, bushings, flexible shafts, casings, electric motors and in the case of pneumatic models, motor vanes. After the identified part(s) were replaced, corresponding vibration measurements were taken under the same work conditions and found to have decreased overall by 16%.

Although each diameter tool had differing median values, these acceleration levels were not statistically different. When the initial readings of knives with higher acceleration levels were removed from the sampling, the median values clustered much closer as shown in Table V.

TABLE V. Standard Deviation (population of all acceleration levels), removal of tools with severely worn parts (>10m/s^2), and removal of tools with moderately worn parts (>5m/s^2)

Tool Diameter (cm)	**Standard Deviation** **Population**	**<10m/s^2 ***	**(m/s^2)** **<5m/s^2 ****
2.858	0.426	0.426	0.426
5.080	3.895	1.370	0.657
6.350	1.396	1.396	1.042
7.620	1.279	1.279	0.900
12.700	1.004	0.703	0.703

* Tools removed with severely worn parts

** Tools removed with moderately worn parts

The foregoing analysis takes into account the various applications where these knives are used since the smaller diameter knives are primarily used to remove meat from bone and tough sinuous parts of the carcass. Whereas the larger diameter knives are operated continuously to remove fat, which is a natural lubricant and thus helps reduce resistance to blade motion.

Conclusions

This proactive study is a first to extensively examine the real-time triaxial vibration acceleration characteristics of a group of various 685 circular cutting knives powered electrically or pneumatically under actual work conditions. These knives are used extensively in the high volume and cold environment of meat processing to remove meat from bone and fat from meat. The study results indicate that neither ANSI S3.34 nor ACGIH hand-arm vibration standards were exceeded. However, those tools, which were poorly maintained and/or had worn parts, corresponding acceleration levels increased; when these worn parts were replaced and the tested tools were properly maintained corresponding acceleration levels were reduced. Thus these study conclusions emphasizes the need to properly and vigilantly maintain and regularly replace worn parts of vibrating hand-tools as part of an overall effort to minimize worker hand-arm vibration exposure.

Although vibration-cold temperatures are documented risk factors which have been causally related to Hand-Arm Vibration Syndrome in numerous medical and epidemiological studies[7, 16] we clearly recognize that in the difficult work environment of volume meat processing there are other potent ergonomic risk factors which can result in upper extremity disorders such as tendonitis, trigger finger and related cumulative trauma disorders which also require additional research. This study is a first step towards realizing that goal.

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Aalborg 2000
Low Frequency Noise and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Threshold of Rattling of Windows and Doors by Low Frequency Noise

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Summary

We made a low frequency noise generation room to know the relations between rattling phenomena and low frequency noise. Auditory threshold and visual threshold of rattling phenomena were measured upon six kinds of Japanese traditional windows and doors with the low frequency generation room. This paper describes thresholds of rattling phenomenon upon these doors, especially Shoji (thin paper pasted sliding door) and Garasudo (sliding door with glass plates). This study makes clear a relation between the rattling thresholds and resonance frequencies, change of these thresholds according to seasons and differences between auditory threshold curves and visual threshold curves.

Introduction

We researched many cases of sufferers caused by low frequency noise. Low frequency noise causes physical and/or psychological effects on sufferers. Many sufferers notice the low frequency noise by rattling of windows or doors (Figure 1). Sometimes they are afraid of the rattling of windows or doors as a sign of an earthquake because windows or doors rattle

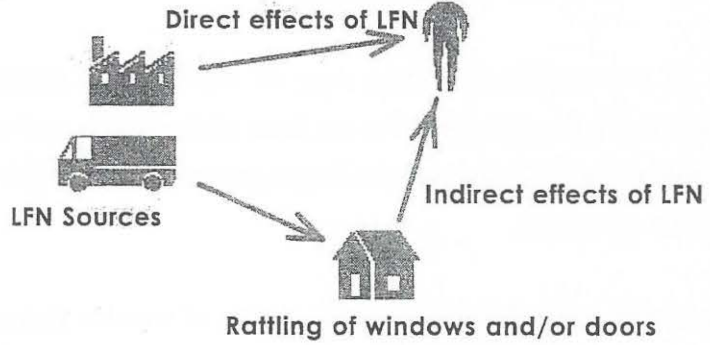


Figure 1. Direct/Indirect effects of LFN

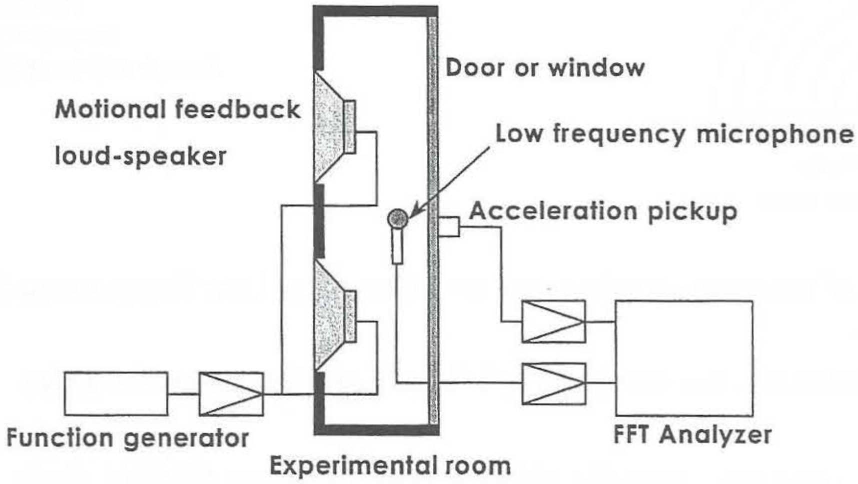


Figure 2. Experimental system

without wind. Therefore we study the relationship between low frequency noise and phenomena of rattling of Japanese traditional doors.

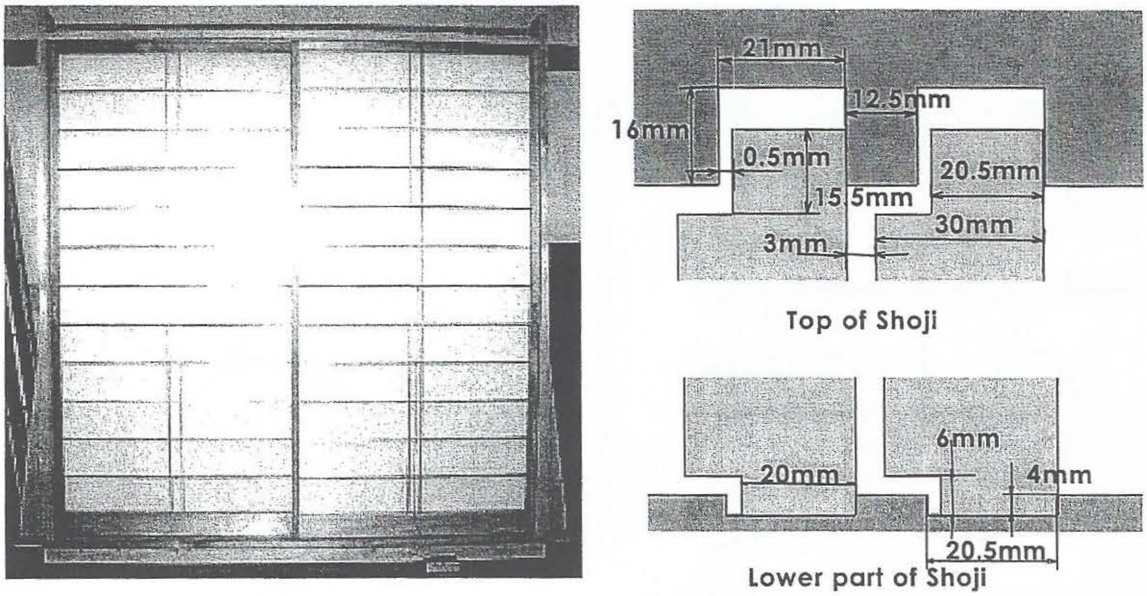
Experimental system and model of doors

Low frequency noise generation room (experimental room) is made as shown in Figure 2. The width and the height of the room are determined by the size of Japanese traditional doors to install two sliding doors in front of the room. There is four 460mm diameter motional feedback loud-speakers on the backside of the room. Special amplifiers drive the loud-speakers with sinusoidal output of a function generator. A low frequency microphone in the room measures the level of low frequency noise loading on doors. A small acceleration pickup, set up at the center of a door, measures vibration acceleration level. Six Japanese doors are measured.

Thin paper pasted sliding door on one side (Shoji)
Sliding door with glass plates (Garasudo)
Thick papers pasted sliding door on both side (Fusuma)
Solid wooden sliding door
Solid wooden rotating door
Wooden rotating door with glass plates

Shoji (Figure 3) is a traditional sliding door of Japan and it consists of wooden flames, wooden beams and a thin paper pasted to the back of the flames and beams. The top of Shoji is caught in a gutter of a lintel and moves along a gutter. The lower part of Shoji slides along a shallow gutter of a doorframe.

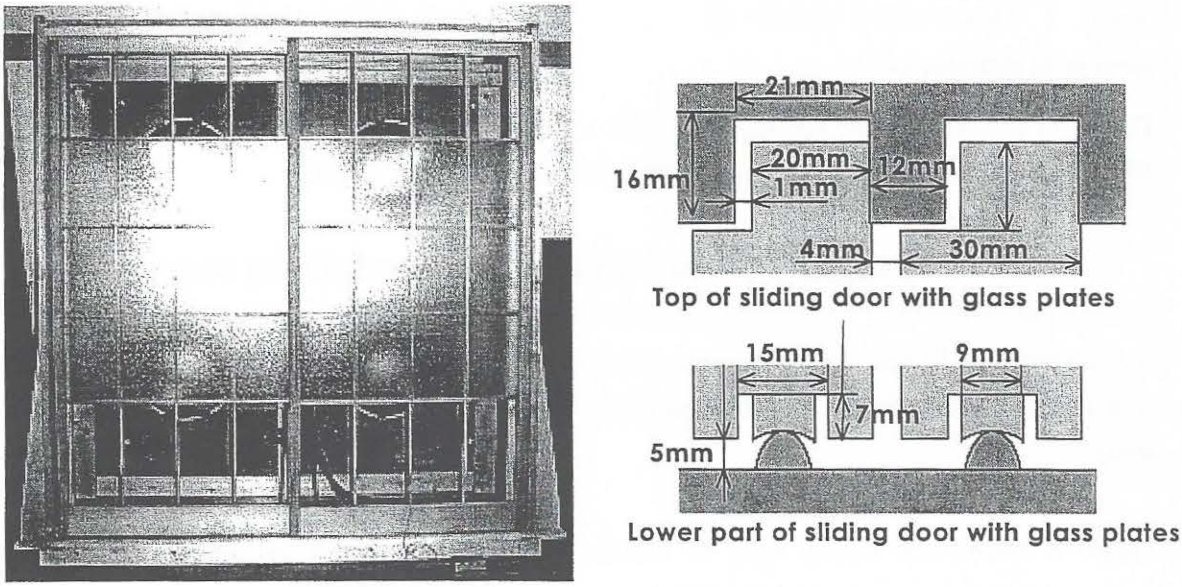
The sliding door with glass plates (Figure 4) consists of wooden flames and five glass plates. The flames have four horizontal beams and three vertical beams. Glass plates are caught



Top of Shoji

Lower part of Shoji

Figure 3. Shoji (thin paper pasted sliding door)



Top of sliding door with glass plates

Lower part of sliding door with glass plates

Figure 4. Sliding door with glass plates

loosely in grooves of horizontal beams. The top is caught in a gutter of a lintel as Shoji. There are two metal wheels under the sliding door and the wheels run on a steel rail of the doorframe.

Fusuma resembles to Shoji. Both side of Fusuma is commonly pasted with thick papers or thin plywood (In the experiment, we used Fusuma covered with plywood).

Distribution of low frequency noise level in experimental room

Distribution of sound level of low frequency noise on a door was measured at nine points as shown in Figure 5. Figure 6 shows the maximum difference in the room at each frequency.

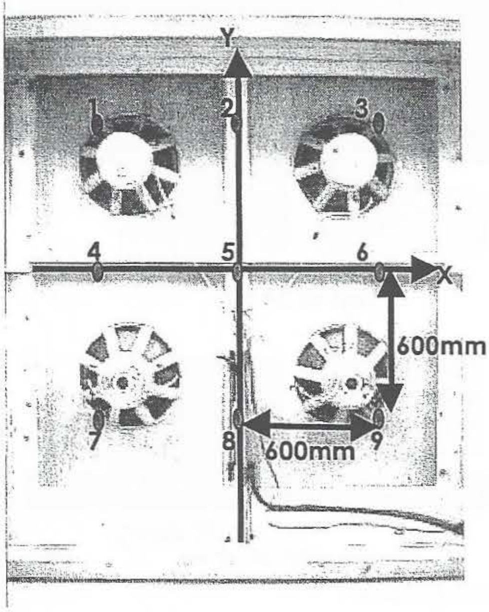


Figure 5. Measurement points of sound level distribution

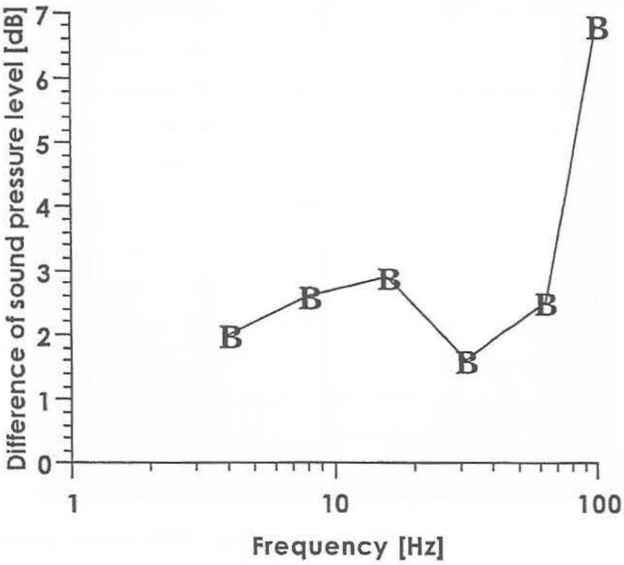


Figure 6. Difference of sound pressure level in experiment room

The level differences are smaller than 3dB under 64Hz, while the differences are large at 100Hz. The experimental room is suited for experiments under 64Hz.

Characteristics of Shoji (thin paper pasted sliding door)

An impulse response of Shoji was measured to know the physical characteristics of the door and is shown in Figure 7. The impulse response was got from vibration by tapping the door with a plastic hammer. It shows the resonance frequency of 13Hz and a gentle peak in nearly 40Hz.

Figure 8 shows the sound level to vibrate the door at 70, 80 and 90dB as vibration

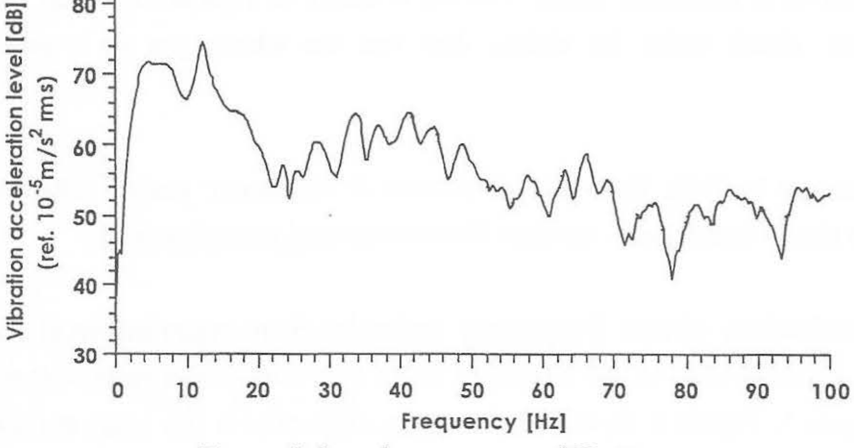


Figure 7. Impulse response of Shoji

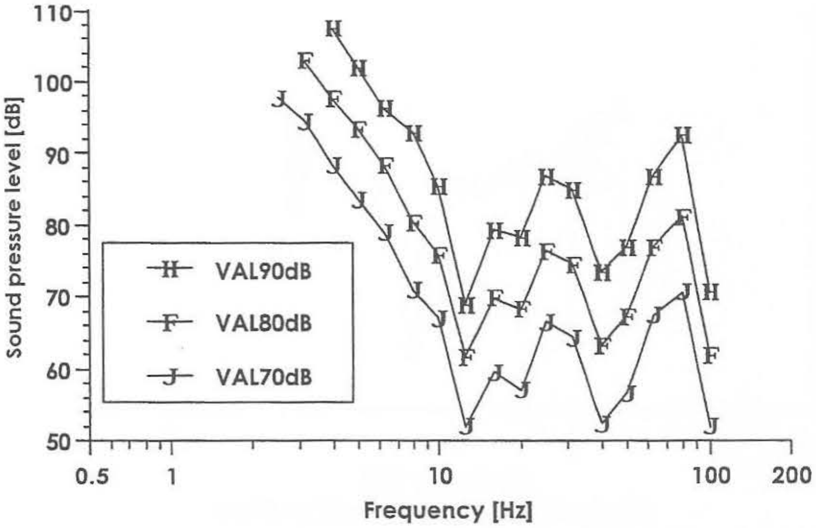


Figure 8. Sound pressure level to vibrate Shoji at VAL 70, 80 and 90dB

acceleration level (VAL, the reference value is 10^{-5}m/s^2 rms according to Japanese Industrial Standard. Add 20dB to convert it into ISO). The vibration level was measured by acceleration pickup set up on the center of the beam of the door. The difference of sound level between the curves is nearly the same at all frequency. Vibration acceleration level rises proportionally to sound level. Frequencies of local minimum of these curves accord with the resonance frequencies of the impulse response.

Figure 9 shows an auditory threshold of rattling. An observer moved his ear near the door and listened the rattling of the door. The threshold is the average level of rising method and descending method. There is two local minimums, 60.8dB at 13.5Hz and 73.9dB at 37Hz. These frequencies of local minimums accord with the resonance frequencies, too.

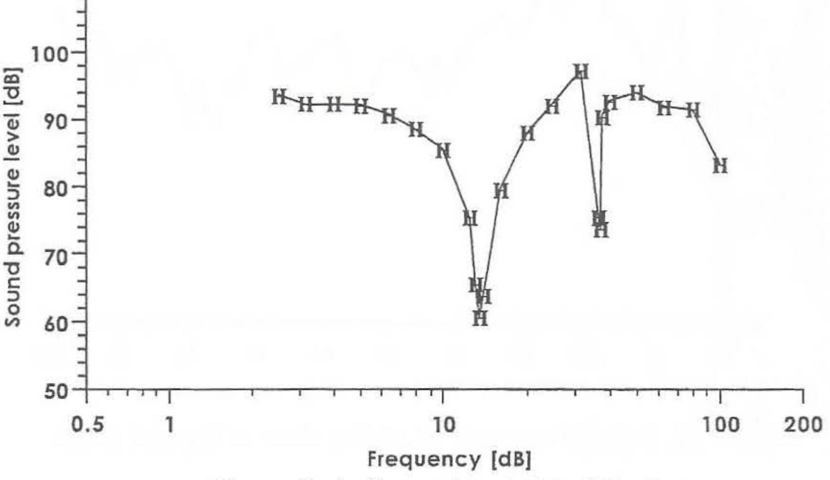


Figure 9. Auditory threshold of Shoji

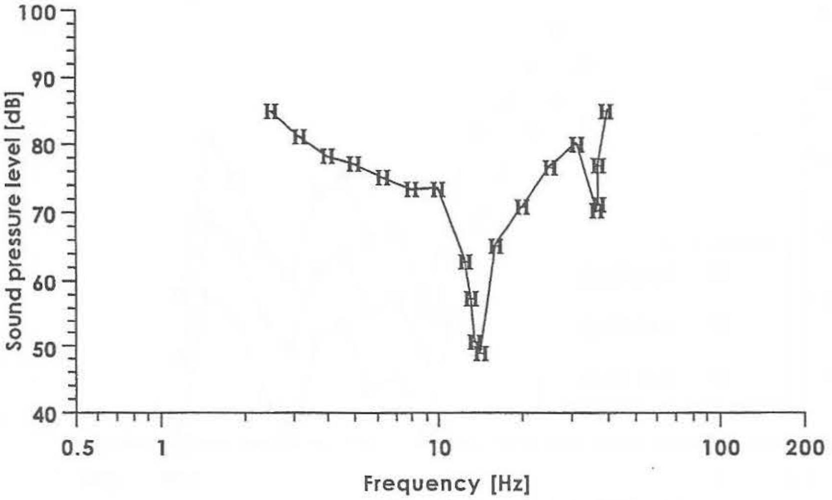


Figure 10. Visual threshold of Shoji

Figure 10 shows a visual threshold of rattling. An observer looked at every part of the door and detected the local vibration by eyes. The visual threshold is the minimum level at which observer can detect the vibration of any part of the door. This curve has also local minimums at resonance frequencies. The levels of local minimums are 49.2dB at 14Hz and 70.5dB at 36.5Hz.

Characteristics of sliding door with glass plates

In many cases, the rattling occurs on sliding doors and windows with glass plates, because the sliding doors with glass plates tend to make rattling easily by collision between glass plates and flames and the rattling noise is easily noticed. Figure 11 shows an impulse response of the sliding door with glass plates. There is a resonance frequency at 6Hz.

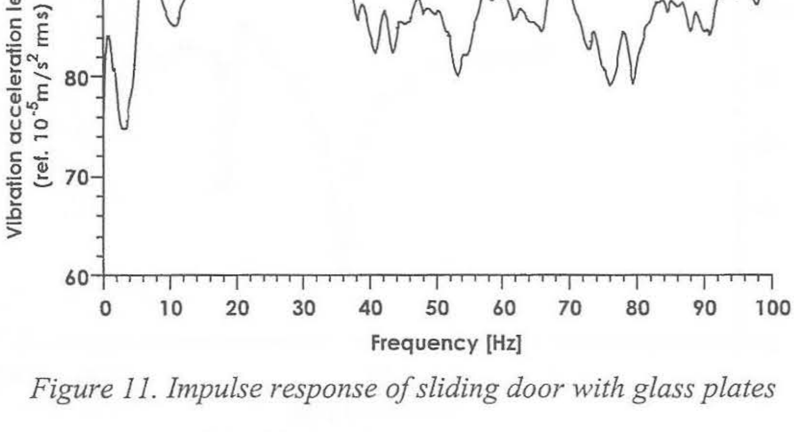


Figure 11. Impulse response of sliding door with glass plates

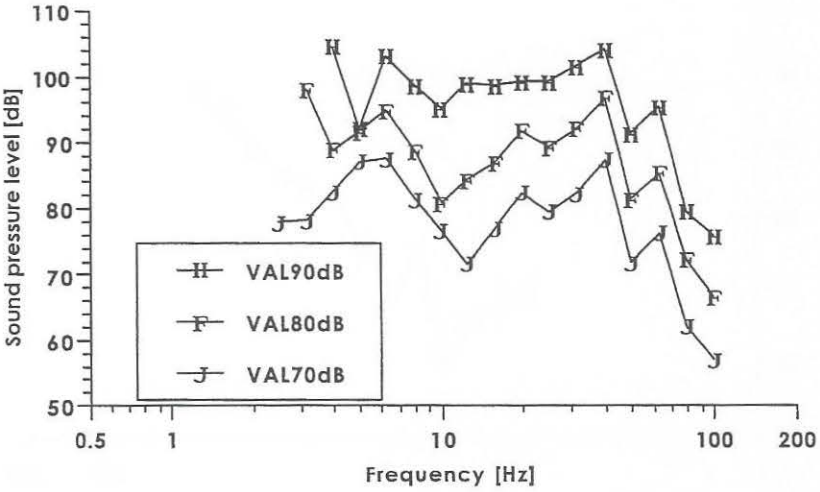


Figure 12. Sound pressure level to vibrate sliding door with glass plates at VAL 70, 80 and 90dB

Figure 12 shows sound pressure level to vibrate the door at 70, 80 and 90dB(VAL). The difference of sound level between the curves of VAL 70dB and VAL 80dB is nearly 10dB at all frequency, however the difference between the curves of VAL 80dB and VAL 90dB is fluctuating. The reason is why the door rattles very loudly at VAL 90dB and the sound level inside is influenced by the vibration of the door.

Figure 13 shows an auditory threshold of rattling. The minimum level was 52.5dB at 6.3Hz. Levels of local minimum are 61.3dB at 10Hz and 70.5dB at 16Hz.

Figure 14 shows a visual threshold of the rattling. The minimum level was 60.5dB at 6.3Hz. This curve has local minimum at 10Hz.

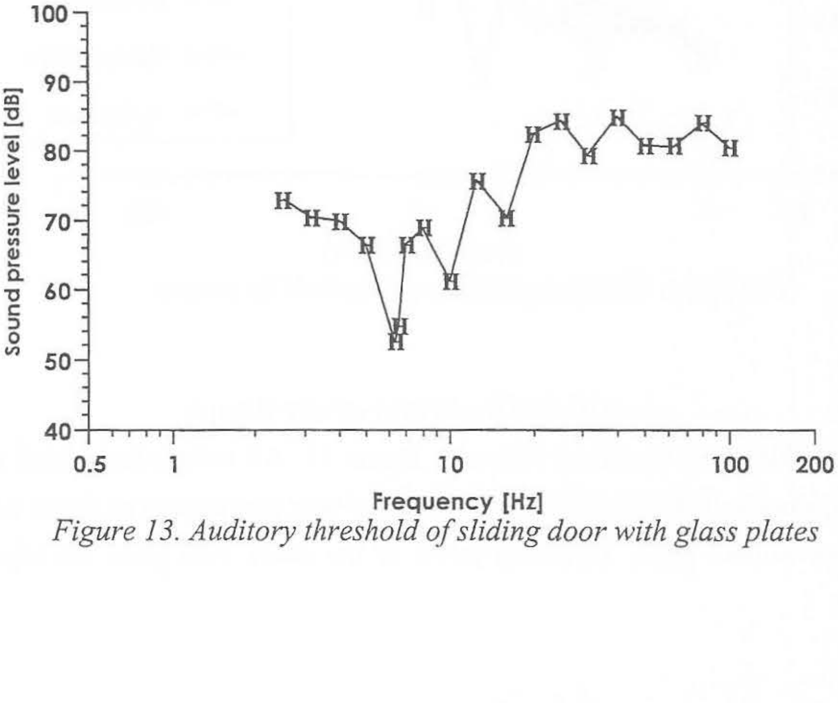


Figure 13. Auditory threshold of sliding door with glass plates

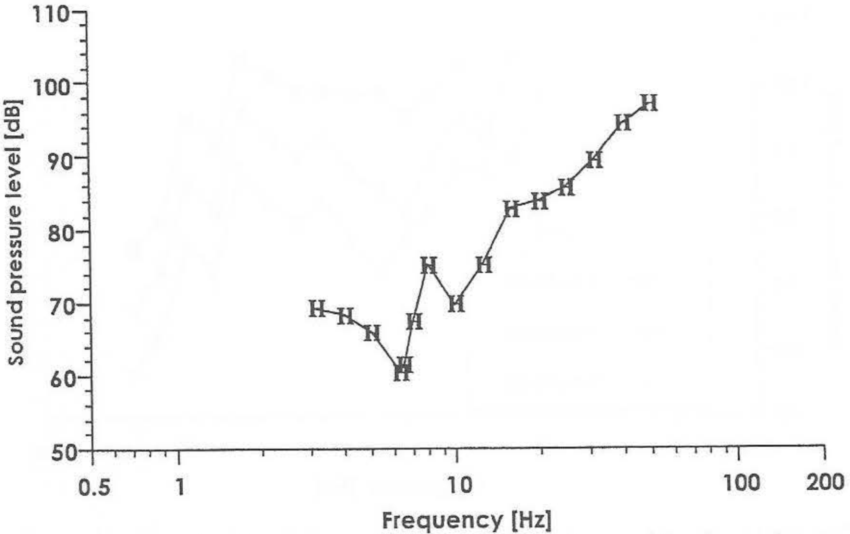


Figure 14. Visual threshold of sliding door with glass plates

It is a common characteristic in these threshold curves that the curves have minimum value at a resonance frequency. All doors show generally the same characteristics, but this door shows a different tendency. Figure 15 shows auditory thresholds measured at various seasons. These thresholds are roughly proportional to frequency and the threshold curves change partly according to seasons. These phenomena probably cause of temperature and humidity.

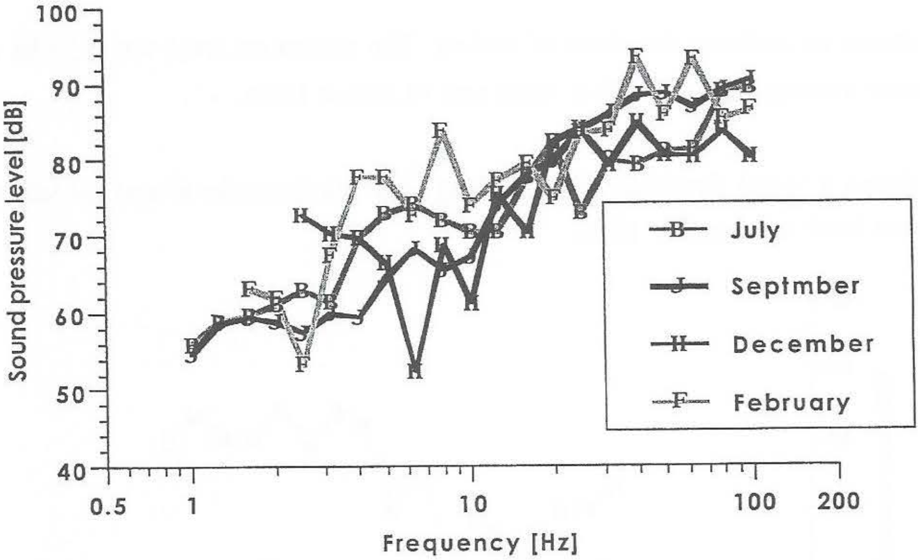


Figure 15. Changes of auditory threshold by season

Auditory threshold of six doors

Auditory thresholds of all doors are shown in Figure 16. All curves have local minimums at resonance frequencies. These curves can be classified into two groups as doors with glass and the other doors without glass. Threshold levels of the doors with glass are especially lower than the other doors. It is the reason that a glass makes noise easily by collision of glass plates and frames. Minimum auditory threshold curve is approximately lined according to the minimum levels of each frequency of all the doors. The gradient of right part of the curve is 5~6dB/oct.

Figure 17 shows the visual thresholds of all doors. These curves can be classified into two groups like auditory thresholds. The gradient of minimum threshold of the right part is 15~16dB/oct. The gradient of visual threshold curves is larger than auditory curves, because the visual threshold depends on the amplitude of doors, while the auditory threshold depends on the velocity or acceleration of doors.

Conclusion

We measured rattling phenomena on various Japanese traditional doors in a low frequency noise generation room and got auditory or visual threshold curves. These threshold curves have the minimums at resonance frequency of each door. Some shapes of the threshold curves change at low frequency part because of the influences of temperature and humidity. The threshold curves can be classified into two categories of doors with glass and without glass. The doors with glass have a tendency to rattle easily at low frequency. Minimum auditory threshold of rattling rises at 5~6dB/oct according to the frequency, but minimum visual threshold of rattling rises at 15~16dB/oct.

These thresholds are measured on Japanese traditional doors. A European door is more tightly made and the threshold of rattling of the European door will be higher than Japanese ones.

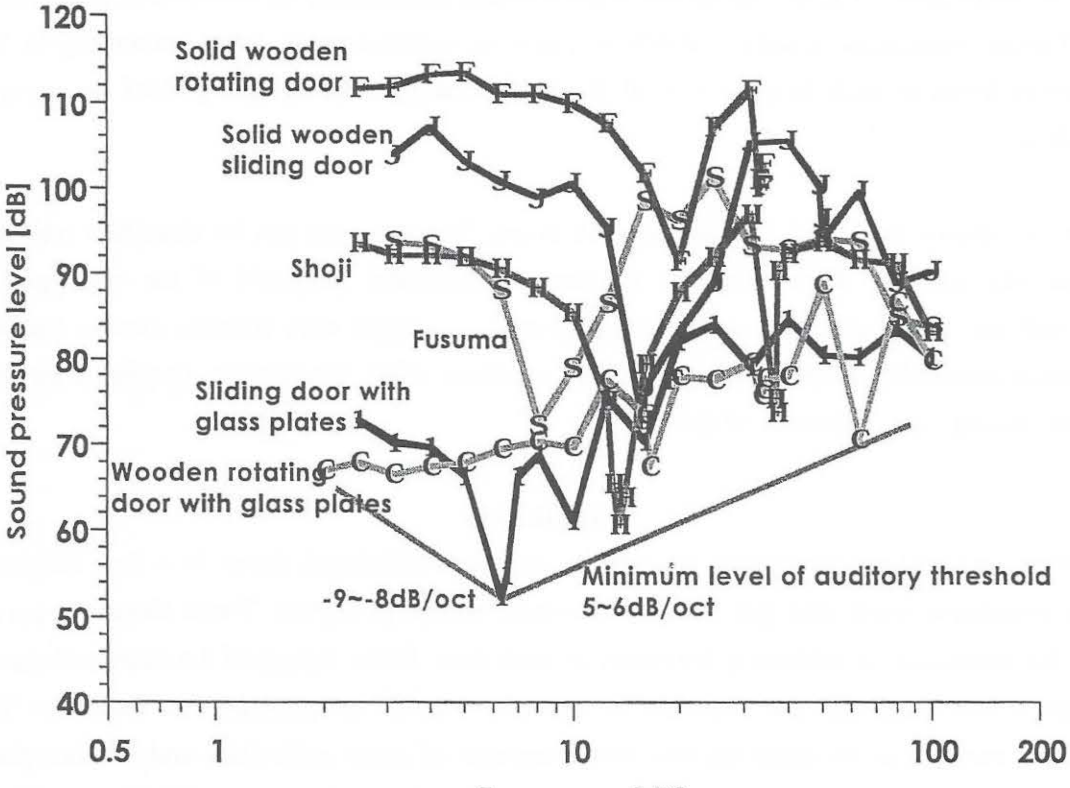


Figure 16. Auditory thresholds of all doors

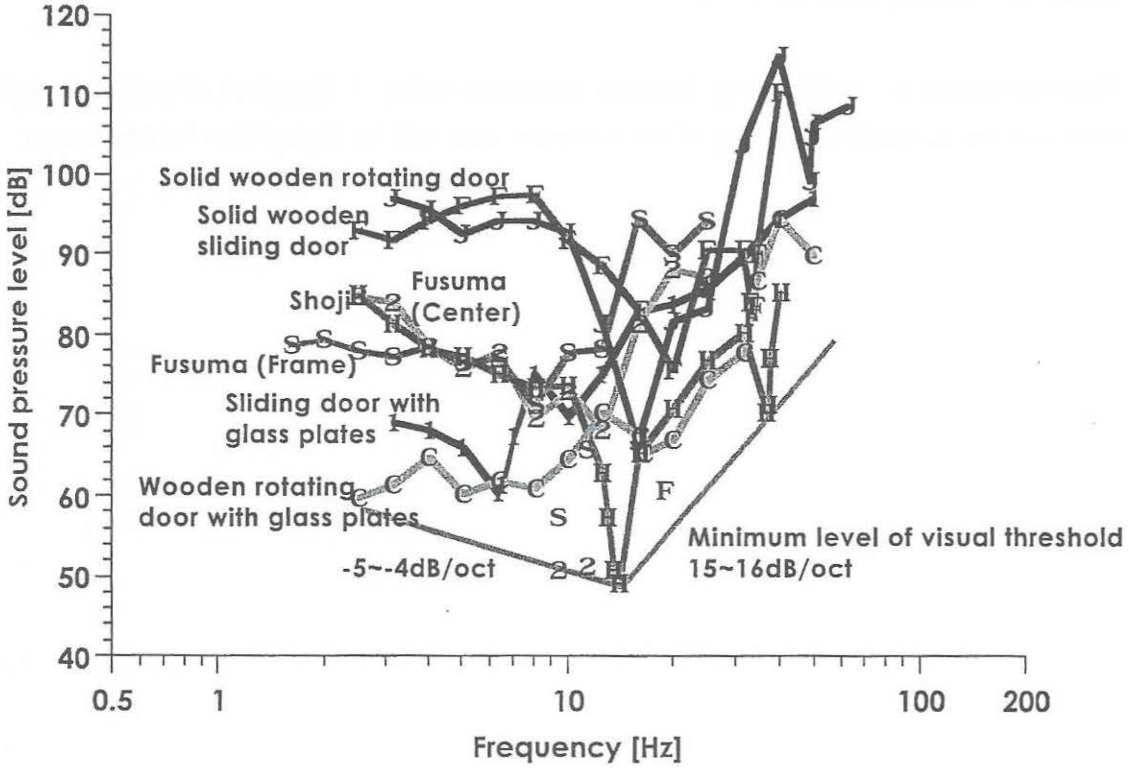


Figure 17. Visual thresholds of all doors

Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Modelling and measurements on ground-borne noise and vibration from railways

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Summary

There is an increasing need for modelling and measurement tools to predict ground-borne noise and vibration, to assess measures and to determine vibration emission from railways. Within the scope of the European project RENVIB some available tools are compared. In the Dutch project L400, a new tool is being developed that by its modularity creates the possibility to combine modelling and measurements. However, none of all these tools are targeted at source or measure assessment and they turn out not to be fit for this. With an alternative framework for describing vibration phenomena, derived from the field of structure-borne sound, this can be overcome.

Introduction

Rail infrastructure is ending up ever closer to residents and people at work. More and more noise barriers are being put up and tunnels built. This development causes an increase in nuisance and damage from low-frequency noise and ground-borne vibration. In new building and railway projects, prognoses and advice on measures are needed. Modelling often provides these. However, the models employed are yet to be validated. Also, a lot remains to be understood about track-soil interaction and reduction measures put at that interface. In this paper, some recent developments are described and a proposal for the assessment of source emission and measure effect is laid out.

Modelling *versus* Measurements: RENVIB II

In order to help railways cope with the increasing demand for environmental ground-borne noise and vibration assessment, the European Rail Research Institute has initiated RENVIB II, a project sponsored by the UIC. Within RENVIB II, railways, research institutes and consultancies co-operate to develop modelling techniques, measures and exchange of measurement results. The first phase of RENVIB II comprised a state-of-the-art study. In the second phase, completed last year, a first step was taken to compare analytical and numerical modelling techniques with measurements on how they assess vibration propagation and the insertion loss of measures.

For sites in Sweden, Holland, Germany and Switzerland, the national railways brought in measurements on soil and track properties and on vibration emission. There were different track types, different soil conditions and different types of measures. Included were measurements on reference track sections.

Two consultancies, AEA Technology Rail and Müller-BBM, used their models to describe these sites and "predict" insertion losses. Each had a different approach regarding the use of the supplied data. One used the vibration results to 'tune' its model in order to enhance the situation description, while the other did not use those results other than to truly validate its model output.

There were some difficulties that impeded measure assessment and the comparison of modelling and measurements.

- Insertion losses are soil dependent. The underlying ground influences the behaviour of the train-track system, of which the studied measures are a part. Also, the propagation in the soil introduces frequency and wave type dependent filtering. The drawback of measurement projects is that measure and reference sections are often not located close enough to ignore a possible difference in soil structure and the impact this has on the vibration generation and propagation. For none of the sites the soil structure and track geometry were determined to such an extent of accuracy that modelling could take the differences between sections sufficiently into account.
- Modelling involved the combination of a suite of (sub)models, each targeted at a different aspect. To assess the reliability of the submodels and the way they are combined, it is not enough to merely compare the end-of-the-line results of the complete model with measurements. For each of the submodels tailor made measurements should be performed. In this project, however, only end results were available from measurements.

As results, vibration levels, or insertion ratio's thereof, were presented for several positions on the ground surface away from the track. A couple of conclusions were drawn from the comparison between the modelling and measurements.

- For stiff soils, modelling and measurements are fairly united in their assessments on the effect of measures below 100 Hz. Neither obtains a high accuracy, however.
- For soft soils it proved much more difficult to relate model outcome and measurement results.
- Ballast description, load spreading, slab-soil interaction and the unification of moving load excitation with roughness/track-geometry excitation are modelling issues which specifically need further development.
- Modelling results are specifically sensitive for the description of the soil (its stratification and material properties) and the slab-soil interaction.
- The analytical description of the train-track system, with roughness/track-geometry as excitation mechanism, seems be the most reliable part of the modelling.
- The distance dependency of measure insertion loss and the relation this dependency has with soil conditions need more attention in measurement campaigns.
- In particular for soft soils, it was hoped that modelling would yield insight into some unexpected measurement results. This insight was not gained.
- Neither modelling nor measurement methods of assessing insertion losses seem to be adequate at the moment. Modelling and measurement practice should be changed towards a combined use of the two. As a first step, measurements should start to include detailed studies of track geometry and soil profiles.

For the assessment of measures, it is undesirable that the soil structure plays such an important role as found in this project. It is not only inefficient and confusing to incorporate a part of the propagation part, as happens now, but it also introduces extra uncertainties and disturbances, like changing soil profiles (measurements) and insufficient soil data (modelling). However, due to interaction between the soil and the track, the propagation path cannot be totally disregarded of either. A general description of source and path are needed to deal with these two conflicting demands on vibration analyses.

Modelling *with* Measurements: L400

In the Netherlands, the public-private institute CUR/COB, founded to further the development of underground building, has initiated a committee to address its vibrational impact. This so-called *L400-committee*, with members from industry, government and research institutes, has developed a numerical/analytical model that describes ground-borne noise and vibration from source to receiver. For each part of this chain there is module that describes its behaviour. The model's strong point is the ability to replace a module with results from measurements.

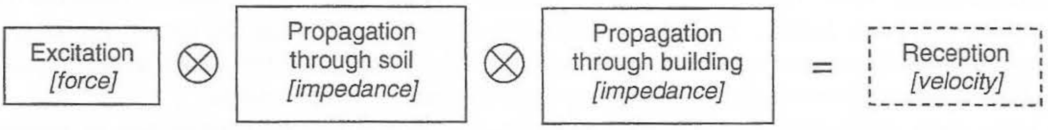

Figure 1: The modular concept of the L400 model is based on the transfer impedance description of the propagation path.

Several vibration source modules (train tracks, piling, etc.) and propagation modules (track substructure, ground, buildings, etc) have been developed. First validation steps are taken. The source modules generate an excitation force spectrum, while the propagation modules produce a spectral transfer impedance matrix between chosen input and output points. Some of the modules are purely analytical, like the ones describing train excitation and ground propagation, while others are generalisations derived from finite element modelling.

Multiplying the impedance matrices with each other, inverting the result to an admittance matrix and multiplying this with the excitation force vector generates a vector that represents the vibration velocity at the reception points. Each of the impedance matrices that the model produces before it starts "solving" the matrix equation can be replaced by an impedance matrix generated by another model or derived from measurements.

It so happens that, quite in line with RENVIB results, the module describing the propagation through the soil is the most troublesome. But, instead of performing measurements to determine soil data needed for the ground module, it might very well be more efficient to perform measurements to create the transfer matrix directly. Combined with the analytical source module and the numerical based building modules a truly hybrid model arises that is fit for, for example, environmental impact studies for new railway tracks.

Lacking either way: source description

For any computational ground-borne noise and vibration prediction detailed modelling techniques are needed, such as the numerical and analytical models employed in RENVIB. For a hybrid approach, where one wants to replace parts of the modelling by measurements, this microscopic description level with its thousands of parameters is not suitable. For that the framework of a macroscopic model is needed, which combines all the calculations into a general, microscopic model independent description. On such a macro level models and measurements can easily be swapped. An example of this is the L400 model.

Besides vibration immission, often rail track emission or the insertion loss of a measure is of interest. Emission levels can be used to compare different track types, can be used for legislation on limits that appreciate the span of responsibility of track users, track owners, land owners and building owners, and for environmental impact studies. For such goals, a source and path characterisation is needed that helps define vibration emission and insertion loss independent from the propagation path. Such a characterisation must consist of parameters that relate closely to the behaviour of a source or the effect of a measure and meanwhile appreciate the coupling that exists between various parts of the source-path system.

Neither the microscopic description level nor the macroscopic level seems to be fit for this task. Parameters such as the vibration velocity field at the interface between ballast and substructure or the force vector that works on the soil transfer impedance matrix, on themselves do not appreciate coupling and only have a complicated physical relation with source mechanisms.

What is needed here is a description of ground-borne noise and vibration on a level in between: a mesoscopic model that has an analytical basis, that can rely on microscopic modelling for the determination of its parameters, that has the model/measurement swappable abilities of a macro model but that contains a source and path characterisation fit for an appropriate vibration emission and insertion loss definition.

In the field of structure-borne sound a candidate model already exists: the source descriptor concept of Mondot[4]. After defining the source – structure interface as the location between active and passive part of the path where actual measurements can be performed, for this interface two parameters are defined. The first one is the so-called source descriptor S and is defined as follows for one contact point with one degree of freedom

$$S = \tfrac{1}{2} v_f \cdot F_f^* \qquad (1)$$

In this equation, v_f denotes the vibration velocity of the contact point of the active and free, unimpeded source, while F_f stands for the outside force that is needed on that free contact point to generate the same velocity. The other parameter is the coupling function C, that describes the interaction between source and receiving structure, and which is defined as

$$C = \frac{Y_p Y_s^*}{|Y_p + Y_s|^2} \qquad (2)$$

The coupling function consists of the source and path point admittances Y at the interface. The product of the two parameters, SC, is equal to the complex power that flows through the connection. Source descriptor S is a power-like quantity that represents an imaginary maximum power flow from the source to the receiving structure. The coupling function C determines how much power actually does flow, depending on the interaction between source and foundation.

However, this concept is not readily applicable to ground-borne vibration from railways. First of all, contrary to machinery in buildings where this concept was first developed for, railway tracks cannot easily be detached from the receiving ground to be performed measurements on. Second of all, although this description is easily extrapolated to more degrees of freedom, the surface excitation and ground propagation calls for a multi wave type treatment in the wavenumber domain.

An alternative but similar concept needs to be designed. Starting from measurability, an alternative interface, power like source descriptor $S_i(\omega,k)$ and coupling function $C_{i,j}(\omega,k)$ should be defined for source and ground wave types i and j. For characterisation tests one can think of pulse excitations. In contrary to structure-borne noise sources, the similarity of train-track systems makes it possible to define the interface closer to the source mechanism without losing generality. With extra instrumentation on track and maybe even train parts, a measurable source quantity and coupling parameter can then be possible.

An example of how this mesoscopic description can help understand vibration phenomena is the problem of Oosthuizen. Near this Dutch town, a vibration measure was applied that turns out to have no effect, especially further from the track. Models and measurements, describing the site with vibration ratios, showed this result eventually, but could not explain it. It is suspected that the measure, although it changed the stiffness of the ground, did not change the power flow. The source descriptor concept would probably show that the measure keeps the source S the same, but increases the coupling C a little bit (because the track admittance was probably lower than the soil admittance to start with), proofing the suspicion.

Conclusions

RENVIB II learned that currently neither modelling nor measurement practise is adequate for assessing vibration emission or insertion losses of measures, mainly because of the role of the propagation path in this. Also, for such assessments and for the prediction of immission levels, hybrid modelling/measuring approaches could help cope with weaknesses in each of such methods. The Dutch model L400 is set up with such a hybrid approach in mind. However, it is focussed on predicting immission levels and gives no new directions for emission or insertion assessments. The design of a vibration description in between the general forces and impedances of L400 and the specific parameters of L400's and RENVIB's underlying analytical and numerical models can be a way out. Concepts such as the source descriptor and coupling function separate source and path in a way that fits the needed description. Determining such parameters by modelling and/or measurements, instead of merely using vibration levels or vibration ratio's can enhance assessment practice and the understanding of ground-borne noise and vibration generation and propagation.

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Aalborg 2000
Low Frequency
Noise
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9th International Meeting
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Proceedings edited by
Henrik Møller & Morten Lydolf

Very low frequency infrasound in railway tunnels

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Summary

In this paper we study the generation and propagation of low frequency infrasound (frequency below 5 Hz) inside railway tunnels. The phenomenon under investigation is triggered by the train's entrance in the tunnel. The train drags along the initially still air and creates a turbulent air velocity field. The energy of turbulence is then transfered to waves which propagate back and forth along the tunnel, eventually establishing a regime of stationary waves at the frequencies of the tunnel's lowest axial modes. Peak pressure levels are usually associated with the reflected wavefront sparked by the head's entrance, and are of order 140 – 145 dB. The peak pressure amplitude increases when the train velocity increases. The largest pressure on record of 152 dB, due to a two-train encounter inside the tunnel, is well below the pain threshold, but comparable to the existing limit for continuous exposures.

Introduction

Although nominally outside the commonly accepted range of audibility 20 – 20000 Hz, infrasound can not only be perceived by the human ear, but they may also lead to discomfort or possibly trigger physical reactions (weariness, dizziness) in exposed subjects (Landström 1988). Ground, as well as air transportation can often generate infrasound. Trains in particular have long been recognized as sources of infrasound, but open-field measurements have failed to show levels in excess of the hearing perception threshold (Landström 1987). Because of their physical and geometrical characteristics, railway tunnels represent instead a very favourable environment for the buildup of high amplitude infrasound, since they behave as excellent waveguides in this frequency range.

In this paper we present and model measurements of low frequency pressure waves aboard tunnel – crossing Intercity (IC) trains. These trains present the most favourable conditions for the occurrence of high amplitude waves, because of their high speed (up to 200 $\mathrm{Kmh^{-1}}$) and the traditional design of cars, which implies a lower degree of airproofing compared to contemporary very high velocity trains (e.g. the TGV in France).

Human sensitivity to Infrasound

Perception. Threshold levels for perception of infrasonic waves in pressure fields have been investigated for several decades. Recent studies (Watanabe & Møller 1990) indicate levels of 87.5 dB at 16 Hz, rising to 99.8 dB at 8 Hz and to 107 dB at 4 Hz. Fewer data exist on the threshold at lower frequencies. Levels found in the literature (around 120 dB at 2 Hz, Yeowart & Evans 1974) might be slightly overestimated, since an extrapolation of the rather shallow rising trend found by Watanabe & Møller (1990) would point to a threshold of order 115 dB.

Annoyance. Because isophonic curves are very closely spaced in this frequency range, it is commonly accepted that the annoyance threshold can be set coincident with the perception threshold (Møller 1984).

Hearing impairment. Threshold values related to possible hearing impairment are more uncertain. For exposures of limited duration (minutes to hours) Tempest (1976) recommends the expression

$$L_T(dB) = 141 - 10\log\left[\frac{f(Hz)}{20}\right] - 10\log\left[\frac{t(\min)}{8}\right]$$

where the last term drops out if exposure is below 8 minutes.

Pain. The pain threshold has been measured at about 155 dB at 4 – 5 Hz and 165 dB at 2 Hz (Tempest 1976). For comparison, the pain threshold for static pressure is of order 175 – 180 dB (0.1 – 0.2 atm.).

All quoted values are relative to continuous exposures. We are not aware of the existence of threshold values for impulsive or intermittent signals similar to the ones found in this study.

Experimental procedure

Mesurements have been performed during the month of October 1999, aboard two IC trains on the Rome – Florence railway line, one northbound, the other southbound. About 15 tunnel crossings have been recorded in each direction. A Brüel & Kjær microphone type 4193 has been positioned inside a 1st class compartment. Given the large ratio of the relevant wavelenghts (at least 100 metres) to the characteristic dimension of the environment (a few metres), the microphone's actual position is definitely irrelevant.

The electrical signal produced by the microphone has been recorded on a Sony PC204 digital audio tape recorder. Off-line signal processing has been performed using a dual channel Ono Sokki 5220 FFT analyser. Time – domain as well as frequency domain analyses have been performed. In order to keep the entire tunnel crossing interval within the FFT analysed range, samples of variable duration have been taken, while a fixed sample lenght of 2048 has been used, so final sampling rates are inversely proportional to tunnel crossing times. Typical frequency resolution is 0.01 to 0.1 Hz.

Results

Turbulent field. Waveforms measured aboard tunnel crossing trains have been found to display fairly regular oscillations, which are more obvious in short tunnels, hinting at the existence of stationary waves. Energy for such waves is provided by the turbulent pressure field created by the train as it drags along the initially still air in the tunnel (Lenzuni, Sisto and Pieroni 2000). The shape of the turbulent spectrum is such that most of the acoustical energy is at frequencies around or slightly below a cut-off frequency f_C. It is a very well known result of fluidodynamics that

$$f_C = \frac{N_S v_T}{D}$$

where N_S is the Strouhal number, D is the tunnel equivalent diameter, and v_T is the train velocity. The Strouhal number appropriate for strongly turbulent flows is about 0.2. Typical velocities of IC trains are 140 Kmh^{-1} to 200 Kmh^{-1}. As for the equivalent diameter, $D = 2(A/\pi)^{1/2}$, where A is the tunnel cross section, which is identical for all tunnels at about 55 m^2, so that $D \approx 8.35$ m. With these numbers one gets $f_C \approx 0.9 - 1.3$ Hz.

Stationary waves. The energy of the turbulent energy field acts as an impulsive source for acoustic pressure waves propagating back and forth along the tunnel. Initially the spectrum of travelling waves is continuous, with amplitudes given by the energy available in the turbulent spectrum, but, after just a few reflections, only those waves with frequencies given by the tunnel's proper modes survive. Because in a tunnel the length L is always much greater than the diameter, the tunnel behaves as a 1-D structure, whose axial proper modes are simply given by

$$f_n = n\frac{c_S}{2L}$$

In our sample, L ranges from 113 to over 3000 m., so characteristic frequencies are mostly in the sub-Hz region, extending to a few Hz in the shortest tunnels. For example, the lowest proper modes of a 400 m. long tunnel (a rather common size on this railway line) have frequencies 0.425 – 0.85 – 1.275 – 1.7 …….. Hz. Because of the good match between f_C and some of the f_n, very large amplitude waves may be excited.

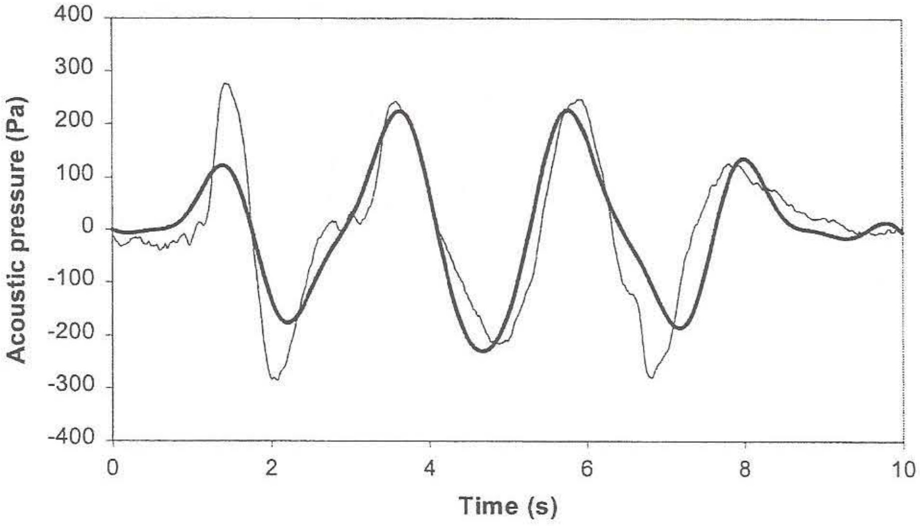

Figure 1: Fast crossing of a 400 m. long tunnel. Shown are the waveform (thin line) and the best fitting linear combination of two modes (thick line)

Fitting the waveforms with a linear combination of the tunnels' proper modes

$$A_n sin(k_n v_T t) sin(k_n c_s t + \varphi_n)$$

confirms the existence of a limited number of high amplitude low frequency stationary waves in the tunnels. In equation (4) the wave vectors k_n have been fixed at their theoretical values $n\pi/L$, while amplitudes A_n and phases φ_n, as well as the train velocity, have all been fitted.

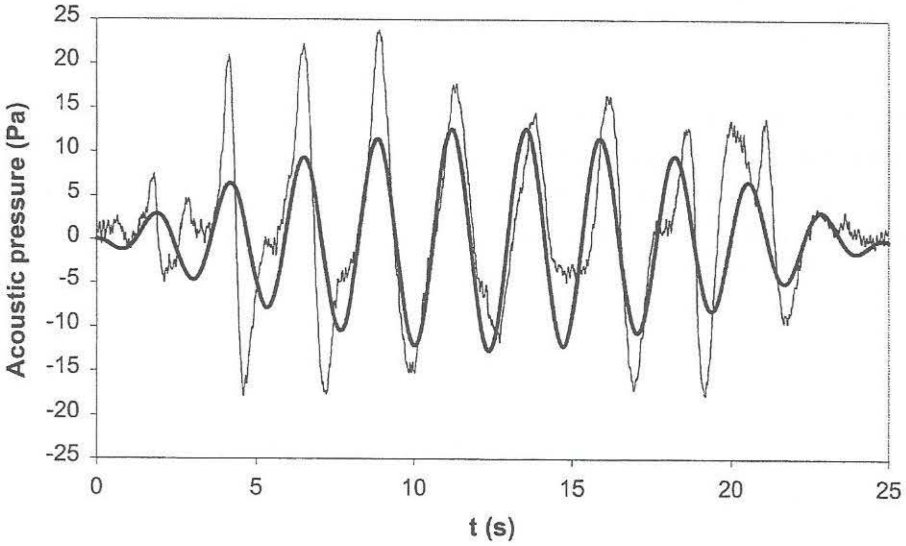

Figure 2: Slow crossing of a 400 m. long tunnel. Symbols as in Figure 1

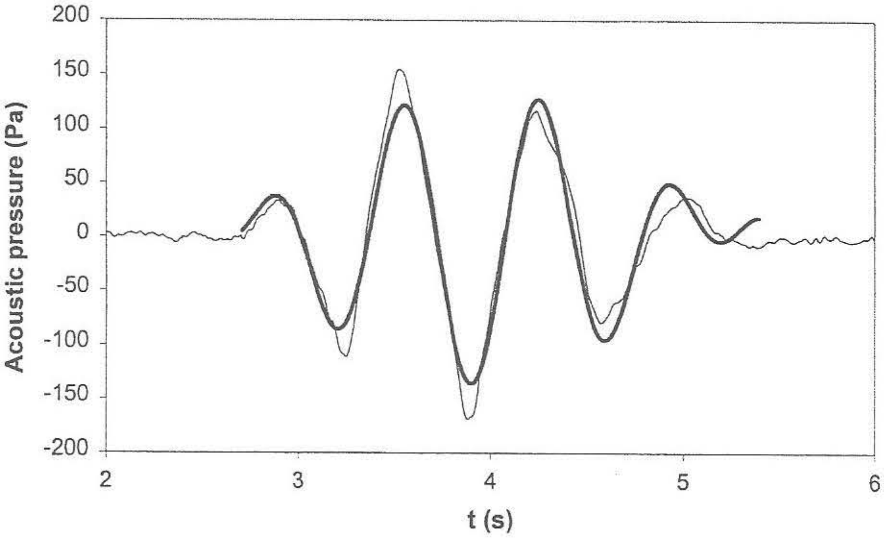

Figure 3: Crossing of a 113 m. long tunnel. Symbols as in Figure 1

Figure 1 shows the measured waveform and the best fitting linear combination of the first two axial proper modes of a 400 metres long tunnel. The best fitted train velocity is 41.7 m/s, in good agreement with the experimental result of 40 ± 2 m/s derived from the known tunnel length and the tunnel crossing time, which is measured with an uncertainty around 0.35 seconds.

Figure 2 shows the waveform due to the passage of a much slower train in the same tunnel. Because v_T is smaller, f_C is smaller and the first axial mode already provides a reasonable fit. Note the much larger number of oscillations and the much smaller values of the pressure wave amplitudes compared to Figure 1. Both effects are clearly due to the smaller train velocity.

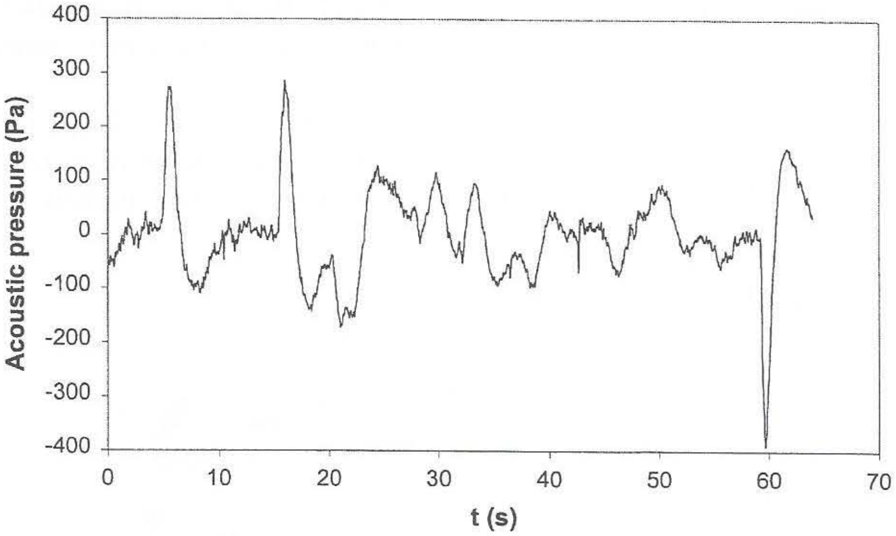

Figure 4: Crossing of a 3000 m. long tunnel.

Shorter tunnels have proper modes with higher frequencies, so fewer of them can be excited. An extreme case is shown in Figure 3, where the first proper mode of a 113 metres long tunnel has a frequency (1.5 Hz) which is very close to the cut-off frequency f_C. Under these circumstances, this mode alone provides an excellent approximation to the waveform.

Longer tunnels have proper modes with lower frequencies, so more of them can be excited. Interference between such modes provides additional complexity to the waveform. The longer crossing time also increases the probability that a train encounter takes place inside the tunnel. The resulting waveform can be very irregular, as shown in Figure 4.

Pressure-velocity relationship. Wave amplitudes depend on the energy of the initial turbulent velocity field, which in turn depends on the train's kinetic energy. It is then reasonable to expect that peak pressure wave amplitudes are correlated to train velocities. Data have been separated according to which of the two wavefronts (excited by the head or tail entering the tunnel) is detected first. This criterion implies the adoption of a critical tunnel length

$$L_C = \frac{H_A(1-\beta)+H_B(1+\beta)}{2\beta(1-\beta)}$$

where H_A is the length of the train section ahead of the microphone, H_B is the length of the train section behind the microphone, and β is the train to sound speed ratio. Given the microphone's location in the train, for typical velocities ($\beta \approx 0.1 - 0.15$) this corresponds to critical tunnel lengths in the range 1350 – 1850 metres. We have taken $L_C = 1500$ m. as the dividing line between "short" ($L < L_C$) and "long" ($L > L_C$) tunnels. Because uncertainties on pressures are negligible compared to uncertainties on velocities, pressure has been assumed as the independent parameter.

The largest wave amplitudes appear in "short" tunnels, where the first detected signal is the one due to the head's reflected wavefront. Data for these tunnels are best fit by a power law $p \propto v^{1.6}$, shown in Figure 5. Figure 5 also shows that data from "long" tunnels and "short" tunnels do indeed occupy separate regions in the log(p) – log(v) plane.

The best fitting power law does not appear inconsistent with data from "long" tunnels, though this sample is too limited in size to draw final conclusions. For any given velocity it also appears that the peak pressure in "long" tunnels is about half as large as in "short" tunnels.

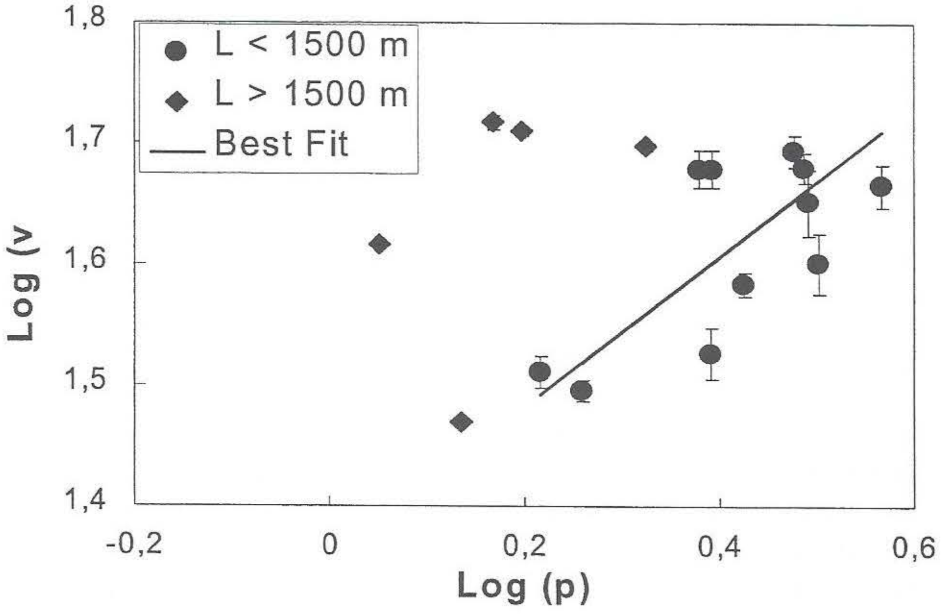

Figure 5: Pressure – velocity relationship in a log-log plane. Show are data for "short" (dots) and "long" (squares) tunnels

Train encounters. Peak pressure wave amplitudes range between 136 and 147.5 dB. A much larger value (152 dB) has been found in one occasion, due to a train encounter taking place near the entrance of the tunnel. Using the pressure – velocity relationship found , one would expect a 9 dB increase due to such an event. This is in fair agreement with the observed 11 dB difference between this value and the average level of peak pressure ampltitudes.

Human exposure. Exposure to very high levels of infrasound occurs over a large fraction of the tunnel crossing time. An average of all tunnel crossings leads to estimate that the level of 140 dB is exceeded for about 30 % of the time, whereas the level of 130 dB is exceeded for about 65 %

of the time. The new Rome – Florence railway line has a large number of tunnels (about 25), most of which in the 400 – 3000 metres range. For typical IC velocities around 45 ms^{-1} and assuming one round trip per day, we find total exposure times of 450 seconds above 140 dB, 1000 seconds above 130 dB. The exposure is clearly intermittent in nature, with relatively short bursts and long rest periods. Lacking any threshold limits for intermittent exposures, we take a value of 143 dB as representative of the 450 – second exposure above 140 dB, and compare this with the value given by equation (1) for a continuous exposure of similar duration. This kind of risk assessment is based on the total energy of the "high end" of the level distribution. The result indicates that we are about 8 dB below the hearing impairment threshold (151 dB). An alternative possibility is a risk assessment based on the largest pressure impluse on record (152 dB). This level is very close to the threshold value given by equation (1). Because the latter applies to continuous exposures, even of limited duration, it should not be used to evaluate impulsive exposures. We feel however that the proximity to the hearing impairment threshold should be interpreted as a warning against underestimating the effects of exposures aboard fast trains. Indeed, any exposure to values in excess of 150 dB, even if occasional and very limited in time, should be carefully investigated. We estimate a 10 % probability that an event of this kind occurs in any Rome – Florence round trip.

Although existing perception thresholds do not extend to frequencies of order 1 Hz, based on a value at 2 Hz around 120 dB (Yeowart and Evans 1974), these should be largely exceeded by typical pressures inside tunnels. We expect that infrasound – induced annoyance effects should be detectable.

Conclusions

- A short set of measurements aboard IC passenger trains has revealed the existence of high amplitude, low frequency pressure waves generated when the train enters or exits a tunnel.
- The train motion induces a turbulent velocity pattern in the tunnel. The associated pressure power spectrum has a cut-off frequency around 1 Hz and a Kolmogorov spectrum with –5/3 slope at higher frequencies.
- The energy in the turbulent field acts as a source for stationary waves which show up at frequencies given by the tunnel's lowest axial proper modes. Because tunnels are quite long, these modes have usually very low frequencies (around and below 2 Hz). Waveforms associated to train crossings can usually be fitted by the lowest (1 to 3) proper modes. The number of modes depends on the train velocity as well as on the tunnel length. Better quality fits are usually obtained for shorter tunnels.
- A very strong resonance has been found in one case where the cut-off frequency of the turbulent spectrum is very close to the frequency of the tunnel's first axial mode.
- Peak pressure wave amplitudes appear correlated to train velocities. The best fitting power law for a sample of tunnels shorter than 1500 m., has the form $p \propto v^{1.6}$
- Peak pressure wave amplitudes range between 136 and 147 dB. One very large value of 152 dB was due to a train encounter taking place in the vicinity of a tunnel's entrance. This is substantially below the pain threshold, but very close to the threshold limit for hearing impairment due to continuous exposures, and largely in excess of the annoyance threshold.

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Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Low frequency noise and annoyance in classroom

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Summary

The aim for this study is to see if students exposed to low frequency noise (LFN) reports to be more annoyed than students not exposed to LFN. Noise recordings were made in 17 classrooms under similar conditions in unoccupied class rooms. The recordings were analysed according to A- and C- weighted levels. Noise recordings were also made in occupied class rooms. The students reported their annoyance in a multiple choice question. The results shows that that there are not sufficient evidence from this material to suspect that the rated annoyance is higher for the LFN exposed students.

Introduction

In 1997 The National Board of Occupational Safety and Health in Sweden carried out a survey on the working environment in Swedish elementary school (7-15 years). All headteachers in Sweden were asked about the working environment at their school. Findings in this survey was that the second most common environmental problem at school is "noise, sound and acoustic problems" (Swedish National Board of Occupational Safety and Health, 1997). Noise exposure problems vary in different school environments due to the presence of different noise sources as well as the variety of activities being carried out. The main effect of noise exposure that has to be considered in the school environments is annoyance.

Holmberg (1997) points out that annoyance as well as negative effects on performance will increase with increasing sound level, tonal character of the noise and variability of the exposure. Differences in responses seem to exist between high and low frequency noise (LFN) exposures. Persson Waye (1995) presents results indicating that annoyance experienced from low frequency noise is higher than from noise without dominant LFN component at the same level. There is also several observations that points out that the A-weighting underestimates the annoyance from LFN (Kjellberg et al. 1984, Persson & Björkman 1988). Leventhall (1980) reports of occurrence of annoyance even if the Leq(A) level is below recommended levels. Still, the most common method for noise assessment and assessment of noise annoyance is the A-weighted level. The Swedish National Board of Occupational Safety and Health (1992) recommends that the background sound level in environments with high permanent demands on concentration and communication should not exceed 40 dB(A) to avoid negative effects as annoyance.

The definition of LFN varies. Dealing with the risk of annoyance a definition is "noise with a dominant frequency content of 20 to 200 Hz" (Persson Waye 1995).
A well known rule of thumb when identifying LFN is the difference dB(C) – dB(A). It is cite in the general advise for indoor noise and high sound levels from the National Board of Health and Welfare in Sweden (SOSFS 1996:7). A limit of 15-20 dB is also given over which the noise is to be considered LFN. The National Board of Public Building points out a difference of 25 dB over which serious annoyance problems are likely to occur.

The aim for this study is to see if the background noise in Swedish elementary school is to be considered LFN due to the criteria in SOSFS 1996:7. Further to test the hypothesis that students exposed to LFN, due to the criteria in SOSFS 1996:7 , are reported to be more annoyed than students not exposed to LFN.

Method

Design. Sound levels were recorded in 17 class rooms chosen at three typical schools in Sweden. Noise recordings were made under similar conditions in unoccupied class rooms with no activity in the class room and normal activity in the surroundings. The recordings were analysed according to A- and C- weighted levels. Noise recordings were also made in occupied class rooms where the students were sitting down working in private. These recordings were analysed according to A-weighted level. Students working in these 17 class rooms were asked to report their annoyance, totally 294 students. The number of students working in each class room was 9-27.

Noise measurements. The noise was recorded using a sound level meter (B&K 2237) with a 1/2" microphone (B&K 4189) and a digital tape recorder (TEAK DA-P20). The meter was placed at an asymmetrical position in the class room corresponding to the ear height of the students. The measurements were made for 10 minutes.

Annoyance rating. The students reported their annoyance in a multiple choice question. Five alternatives were given from "Not at all annoying " to "Very annoying".

Data treatment. To test the hypothesis that students working in class rooms with LFN are reporting to be more annoyed than students working in class rooms without LFN a Simple Factorial ANOVA model is used. To achieve statistical control of potential confounding variables in the samples background sound level, activity sound levels and numbers of pupils was entered as covariates in the model.

Spearman rank order correlation was calculated to display the relationship between reported annoyance and A-weighted background level and A-weighted activity noise level.

Results

Class room	$L_{eq(C)}$	$L_{eq(A)}$	dB(C)-dB(A)	LFN-Exposure	dB(A)-Activity	Number of students
1	48	37	11	Not Exposed	49	16
2	51	36	15	Not exposed	50	12
3	58	39	20	Exposed	51	14
4	61	38	23	Exposed	52	18
5	52	37	15	Not exposed	54	19
6	53	40	12	Not exposed	56	16
7	56	34	22	Exposed	56	18
8	60	39	21	Exposed	59	11
9	52	43	10	Not exposed	60	9
10	54	40	14	Not exposed	60	23
11	50	38	12	Not exposed	60	13
12	58	35	23	Exposed	61	21
13	54	34	20	Exposed	62	16
14	60	39	21	Exposed	63	22
15	50	40	10	Not exposed	64	13
16	60	40	21	Exposed	66	24
17	60	40	20	Exposed	68	27

Table 1: $L_{eq(A)}$ and $L_{eq(C)}$, dB(C) – dB(A) difference for unoccupied class rooms. $L_{eq(A)}$ during class, number of students fore each class and categorisation of classes exposed and not exposed to LFN due to SOSFS criteria.

Table 1 shows that only one class room exceeds the recommended background sound level of 40 dB(A) Leq in environments with high permanent demands on concentration and communication stated in AFS 1992:10.

The comparison of reported annoyance between the LFN-exposed students and students not exposed to LFN using background sound, sound level during class and number of students as covariates shows that there are not sufficient evidence from this material to suspect that the rated annoyance is higher for the LFN exposed students (F=1.18 p=.32).

None of the covariates explains the variance in reported annoyance. Background sound level (F=2.79 p=.10), sound level during class (F=2.34 p=.13), number of students (F=1.24 p=.27). A result supported by Spearmans rank order correlation test showing that the distribution of reported annoyance does not depend on the distribution of the A-weighted background level (r=-.07 p=.22). The distribution of reported annoyance does nor depend on the distribution of the A-weighted activity noise level (r=.07 p=.26).

Discussion. The recommendation in AFS 1992:10 that the background sound level in environments with high permanent demands on concentration and communication should not exceed 40 dB(A) to avoid negative effects as annoyance is only exceeded in one of the cases. The statistical analysis of this material points out that there are not sufficient evidence to suspect that the reported annoyance is higher for groups exposed to higher background and activity sound levels.

Founded in the statistical analysis the hypothesis that students exposed to LFN, due to the criteria in SOSFS 1996:7 , are reported to be more annoyed than students not exposed to LFN has to be rejected.

If the SOSFS-criteria is used to classify LFN-exposure the nine groups exposed are not reported to be more annoyed than groups not exposed to LFN. In fact the analysis indicates that the A-weighted back ground level and the A-weighted activity sound level is more critical according to reported annoyance. However, results do not reject the proposed method for defining the LFN component, neither that this definition is a relevant method for the risk assessment of LFN annoyance. The school environment is very complex and there are lots of factors that will influence the annoyance response, not only physical factors. More of these factors has to be considered assessing the effects of noise annoyance in school environments. It is justified to continue further studies into this area before dismissing low frequency noise as a critical factor in the school environment.

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Aalborg 2000
Low Frequency
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Proceedings edited by
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Perception of the public of low frequency noise

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Summary

This paper describes the results of a series of measurements using a variety of systems comprising vibration sensors and sound-level measuring devices. These were carried out at homes of sufferers from low frequency noise and other environments where low frequency noise was likely to be generated. Suggestions are made as to the possible reasons for the perception of low frequency noise by sufferers.

Introduction

This paper is based on work done by the Low Frequency Noise Sufferer's Association, (LFNSA). This is a U.K. Organisation which Sufferers of Low Frequency Noise and people working on the problems are invited to join. During the past ten years some 500 people have been Members, most of whom have experienced Low Frequency Noise (LFN), or are connected to people who are sufferers.

A programme of research was started early in 1997 with the aim of finding out:

1) why people are affected by LFN,

2) what improvements could be made to detection due to the increase in the sophistication of detection instruments, and their appropriate deployment.

3) the necessary mechanisms, both legal instruments and physical procedures which might provide solutions to the problems created by LFN.

Measurement Systems

System A The measurement device (GEOSENSE PS1, originally used by the US Defence Department) is an electronically modified monoaxial geophone element. This incorporates a sensing element which vibration sensing element which uses a magnetic core inside a coil. The coil is fixed relative to the case of the meter and therefore the vector of the incident vibration, whereas the seismic core stays relatively stationary because of its mass. There is therefore relative movement between the coil and its core. An emf is generated by the instrument that is the electrical analogue of the incident physical vibration. The low frequency response of the geophone element is digitally enhanced to give a response flat to below 1 Hz. The output emf is fed via short shielded leads to an FFT analyzer. Fig 1 shows two sets of measurement using this system, the first one taken in a house known to be quiet at Low Frequencies and inspected by many LFN Sufferers, and the other taken in the home of an acute LFN Sufferer.

System B This is an airborne analyzer using the microphone channel of a VIBROSOUND 6-channel, 24-bit digital recording system (made by MAGUS Electronics, Sandbach, UK) fed from the output of a Bruel & Kjaer Sound Level Meter fitted with a microphone that has a flat response down to 1 Hz, (fig 2).

System C This uses a LENNARTZ low-frequency, three-component digital trial seismometer to detect vibration with the output fed to the VIBROSOUND instrument for recording and later analysis and display, (fig 3).

System D This system, first deployed in mid 1999, uses a CEL 441 Sound Level Meter, working directly into an ONO SOKKI FFT analyzer. It is generally accepted that a tonal sinusoidal signal must have about 100 cycles before it can be recognised by an analogue detector as a clear peak with a Q" factor of 40 dB. For a 4 Hertz signal, this represents a sample time of 25 seconds. The ONO SOKKI system described in this paper only has a sampling time of 1 second and therefore, as seen, has a resolving power acceptable only above 20 to 30 Hertz, whereas for 100 repetitions the frequency would have to be greater than 100 Hz. Therefore the ONO SOKKI cannot adequately resolve the total spectrum of the incident LF signals. Fig 5 shows the display for a noisy and a quiet situation.

System E This system uses an FFT analyzer developed for the British Aircraft Corporation and the MOD (UK) which displays the analysis in bands of 0.55 Hertz width, (fig 4).

System F This utilises a small accelerometer fixed on a window pane which acts as a vibration sensor for signals induced in the pane by the airborne signals. Its output is recorded on the VIBROSOUND for subsequent processing and analysis.

Detection

On the basis of experience and the analysis of the vast amount of information provided by sufferers, it was decided to look at signals in the band 2 to 40 Hz, deploying both vibration meters, and sound level meters. The reasons for this decision are:

1) the normal range of human hearing is such that the response falls rapidly below 40 Hz, which results in only a small percentage of people being affected by signals in this range, and

2/ standard equipment issued to Environmental Health Officers (EHO's) does not respond at all well to those frequencies because of the A-weighting of the response and when they are deployed inside buildings. As they cannot record the noise, they are unable to act on the nuisance claim.

Often when they do get a reading, the use of an A-weighted electronic filter severely attenuates the value of the low frequency signals in dB. Their professional organization and also the Department for The Environment, Transport and Regions (DETR) advise against the use of this A-weighting and this is a view supported by a number of respected researchers, past and present. The reasons for eschewing the use of A-weighting at low frequencies, is based on the different way the human perceives noise at low frequencies compared with its perception at middle and higher frequencies.

Deployment

In this study seismometers have been deployed where they are able to detect the nodes and antinodes of vibration caused by LFN, at various levels in a building from foundation to roof, and also in the ground outside a building and on the top of posts, two meters high, planted outside the building. These latter are used to determine whether or not the signal is groundborne, airborne, or both; and data from the vibration meters are compared to data from meters designed to respond to changes in air pressure level whilst discriminating against vibrational signals. These air pressure level meters are typically Bruel & Kjaer Sound Level Meters. At low frequencies, these meters require an acceleration of 1 meter per second per second in order to produce an equivalent sound level pressure output of 67dB. Such a reading in decibels is a relatively small noise reading in the low frequency band compared to the massive acceleration required to produce it.

Discussion of results

All these systems detect and display tonal peaks from frequencies 2 to 40 Hz, or the upper limit of the system used.

Sound Level Meter The unweighted linear levels can he as high at 60 decibels. However, if A-weighting is then applied much reduced levels including some that are negative may be produced which is clearly unsatisfactory. Many of the C-weighted results from the ONO SOKKI/CEL (system E) are summarised in Fig 6, and it is seen clearly that between 4 and 12 Hz the filtered level in a quiet house is some 10 dB lower than the unweighted.

Vibration Meter Levels The levels displayed show peaks of velocity ranging between 0.1 to 1 Nanometres per second in quiet environments, and from 1 to 50 Nanometres per second in noisy environments.

Sample time and tonal resolution We investigated the resolving power of each of the several systems used and as expected longer periods of sampling produced sharper peaks, better resolved peaks on the frequency spectrum chart. The resolving power is very important at low frequencies because of the necessity to discriminate interference between two close tonal signals in frequency.

Potential for annoyance Fig 7 shows the well established equal loudness curves and the close proximity of these curves at low frequencies should be noted. This is important and is one of the reasons why A- weighting should be avoided. It is clear that the level of perception and annoyance could he about 10 dB apart in the range 2 to 12 Hz.

Residual Background Some recent results from other workers on LFN in the UK have shown that even with the co-operation of large industries in shutting down industrial plant (a complete windfarm in Cornwall, and a major steel works in Wales) residual noise levels exist. These show up on most frequency analyzer displays, (as long as they have a bandwidth which extends down to down to near dc) as a large value at dc falling exponentially as the frequency rises, (figs 2, 4, 6, 9). Many recording Engineers have come across this problem and insert low-pass filters with rolloff at about 30 Hz to get rid of the low frequency rumble.

Fig 8 shows the frequency spectrum from a Sound Level Pressure meter deployed inside the Liverpool Anglican Cathedral, one of the largest Gothic buildings in the world where the walls and internal vaulting are of massive blocks of stone with supporting flying buttresses. The high level generally seen at low frequencies (as a falling exponential as the frequency rises) was not observed during this experiment. It may be the case that such a massive structure may be able to filter out these lowest frequency signals.

Table 1 tabulates the responses of 15 typical Sufferers situated in a particular valley. Very similar responses were discovered. The effects of random frequency changes were described as dronings, rattles, and tingles. System D which had a sample time of about seven seconds found peaks that altered suggesting that variable "beats" could be the cause of the sensations so experienced.

Resolving power of the brain

The reports from LFN sufferers would appear to suggest that the most efficient device for detecting Low Frequency noise may well be the human brain. This borne out by careful questioning of LFN Sufferers. A very important point that arises out of the evidence gathered, is that, often a Sufferer is unaware of LFN until that person has been in the acoustic field for several hours or days. In fact the sufferer then often becomes sensitised and can then not voluntarily exclude the noise source. The output of the brain's analysis of infrasound is usually, the generation of heard effects, but visual disturbances have also been reported and it has been suggested that some apparently paranormal sightings are in fact caused by infrasound.

For future work some thought should be given regarding the use of devices that have very long sampling times, say many hours, so as to simulate the brain. Based on the discussions we have had with Sufferers, and the ability of the brain to store, process, and produce subjective Psycho-Acoustic Effects, we have no doubt that the memory of the brain is able to hold acoustic information for several hours.

Analogues from musical acoustics

For many centuries Musicians have produced an effect which may partly explain why some people dislike the effects of LFN. Low frequency musical instruments such as the Double Bass and Pipe Organs use two LF Notes such as C and C in the CCCC Octave or notes at 16.25 and 24.5 Hz, which produce beats with a note of 8.25 Hertz. In Churches and Cathedrals the use of this double note was to stimulate emotion during the playing of the organ, during hymns, psalms, processions, or as a background. It was found generally, that low frequency tones were felt rather than heard and were translated into deep feelings of awe, and worship of a great unseen power. This could explain the awesome and fearful effects of powerful LFN on human perception.

Powerful industrial LFN sources have been shown to produce tonal noise which will set up a large number of beat frequencies (Rushforth et al 2000).If one or more of the beating signals varies this would account for the effects described as droning, pulsing, phasing, and the vibrating of the inner ear. Tones about 1 Hz apart in frequency may well produce the rattling effect described by some Sufferers.

Conclusions

Several different experimental systems have been used variably to detect, process, and display, LF signals presented as

1/ vibration in the structures, or in the foundations of various buildings, due to the impact of airborne waves or groundborne waves, respectively.

2/ sound level pressure changes due to incident airborne waves, or secondary air borne waves generated by the vibration of the structures of the buildings.

3/ Care should be exercised in the use of Sound Level Pressure Meters inside rooms where the dimensions are less than one half of a wavelength of the incident wave. A simple consideration of this system will show the solid materials in the structures vibrating in phase, and the observed signals may well result only from minor phase changes and distant reflections. System F detected vibration levels on window panes of the order of .01 ms^{-2}, (fig 9). Windows act as the diaphragms of large loud speakers, and may well be responsible for high levels of LFN detected by this system and by Sound Level Pressure Meters placed in line with the source via the windows.

Very high background levels of infrasound have been detected in urban areas, country areas close to windfarms. It appears that the familiar exponential backgrounds comprising 1 to 15 Hz tonal noise levels are rising throughout the UK. Similar trends have been reported from Europe. There is presently no legislation in force regarding the controlling of LFN. It would be useful to have NOISE MAPS of all areas of a country using the same procedure as used in Birmingham.

Acknowledgements

The Authors would like to thank members of Liverpool University staff, especially I. Rushforth, and Dr A Moorhouse. Thanks are also due to some 100 Members of the LFNSA for taking part in experiments and allowing their homes to be used for test purposes. We thank the National Lottery Board for a grant for measuring equipment and we are grateful for the support via private donations from Sufferers.

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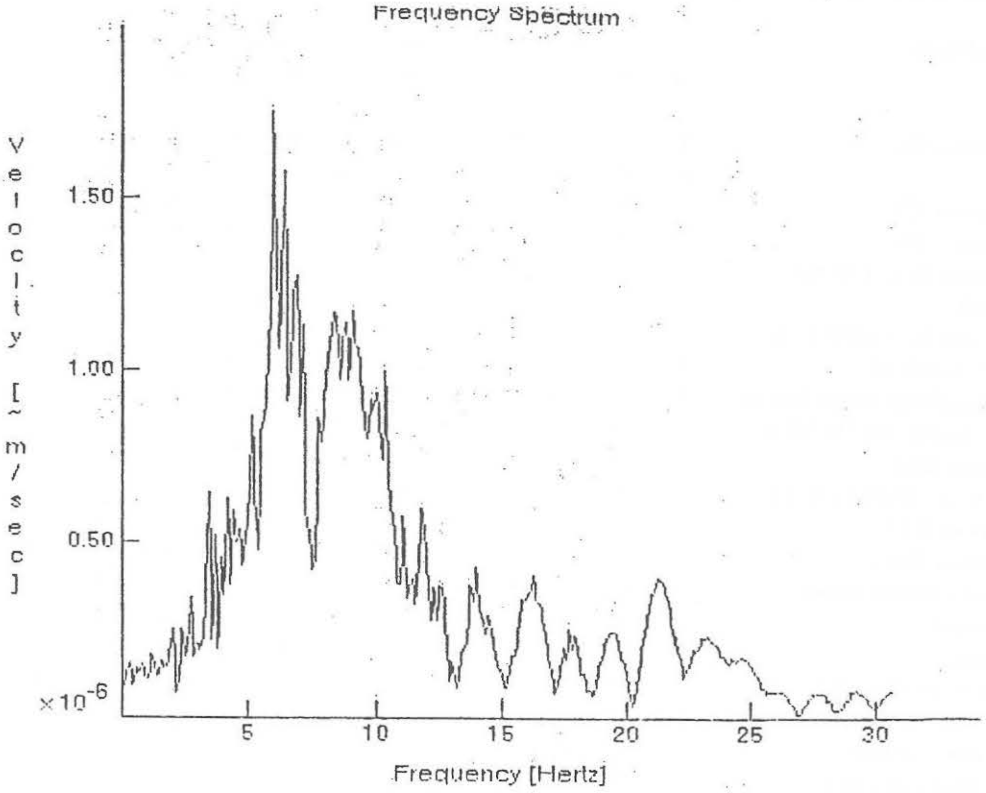
Survey of a cross-section of People Suffering from the Noise in the Stretton Valley

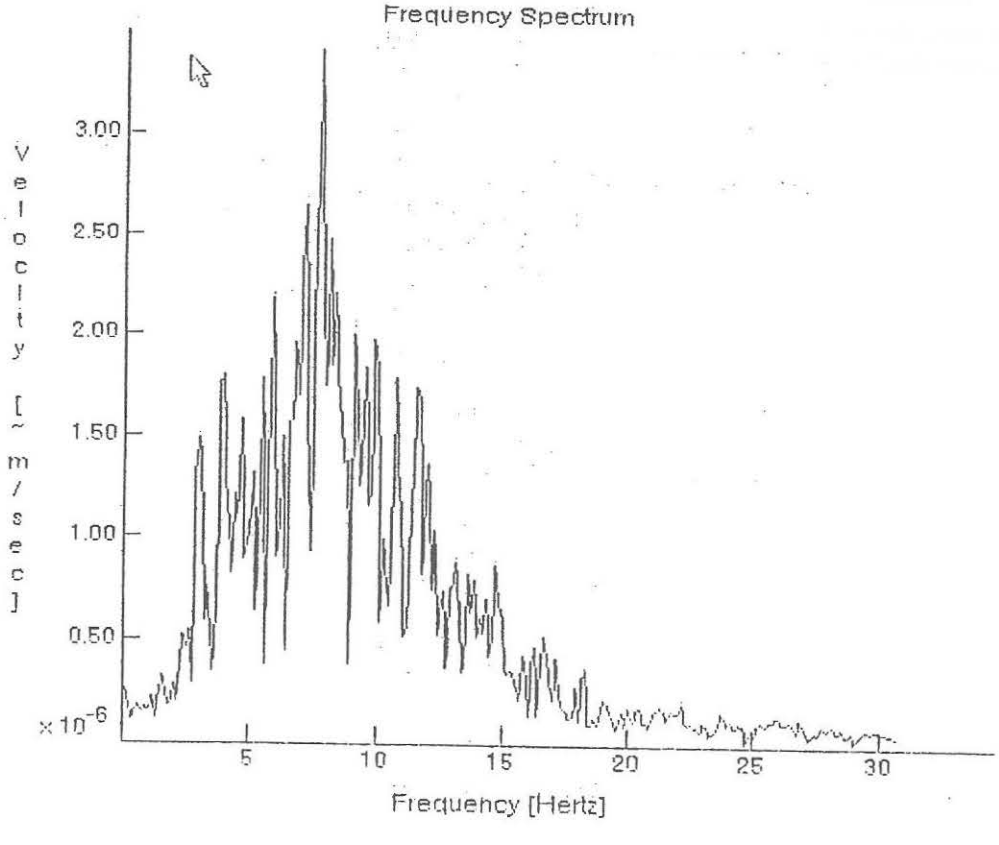
Y...Yes.........N.,.No M,,,Male; F...Female

QUESTION	1	2	3	4	5	6	7	8	9	10	11	12
Male/Female	F	.F	F	F	M	M	F	M	F	M	F	M
AGE	40	60	53	40	38	66	64	55	57	60	45	66
Consulted GP?	Y	N	N	N	N	N	N	Y	N	N	N	N
Hearing tests	N	N	N	N	N	N	N	Y	Y	N	N	N
How long heard NOISE YEARS	2.5	2.5	3.5	-	3	8	8	8	2.5	2.5	2.5	3
Been told its TINNITUS	N	N	N	N	N	N	N	N	N	N	N	N
E.H.O.Involved	Y	N	N	N	N	Y	Y	Y	N	N	Y	N
Any Readings taken Sound.	N	N	N	N	N	N	N	N	N	N	Y	Y
Noise heard NIGHT/DAY	N	N	ND	D	ND	N	N	ND	N	N	DN	DN
In home only	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
PAINS ACROSS HEAD	Y	N	Y	Y	Y	N	N	Y	Y	N	Y	N
HEADACHES	Y	N	Y	N	N	N	N	Y	Y	N	N	N
Disturbed Sleep	Y	Y	Y	N	N	N	N	Y	Y	N	Y	N
Lack of concentration	Y	Y	Y	N	N	N	N	Y	Y	N	Y	N
Depression	N	N	Y	N	N	N	N	Y	Y	N	Y	Y
Dissiness	Y	N	Y	N	N	N	N	N	N	N	Y	Y
Any serious illnesses?	N	N	Y	N	N	N	N	N	7YRS	N	N	Y
Bungalow/house	H	H	H	B	B	B	B	B	H	H	H	H
Near slope of hill	N	Y	Y	N	N	N	N	N	Y	Y	N	N
Noise fealt elsewhere	N	N	N	N	N	N	N	N	N	N	N	Y
EFFECTS OF BEATS T...JINGLING EFFECT,	Y	Y	Y	Y	T	Y	Y	Y	Y	Y	Y	N
Noise like a machine M...LIKE RATTLING MARBLES	Y	Y	Y	Y	M	Y	Y	Y	Y	Y	Y	N

Table 1

A… Quiet





B… Noisy as perceived by Sufferer

Fig 1 Seismometer Readings at POOLE

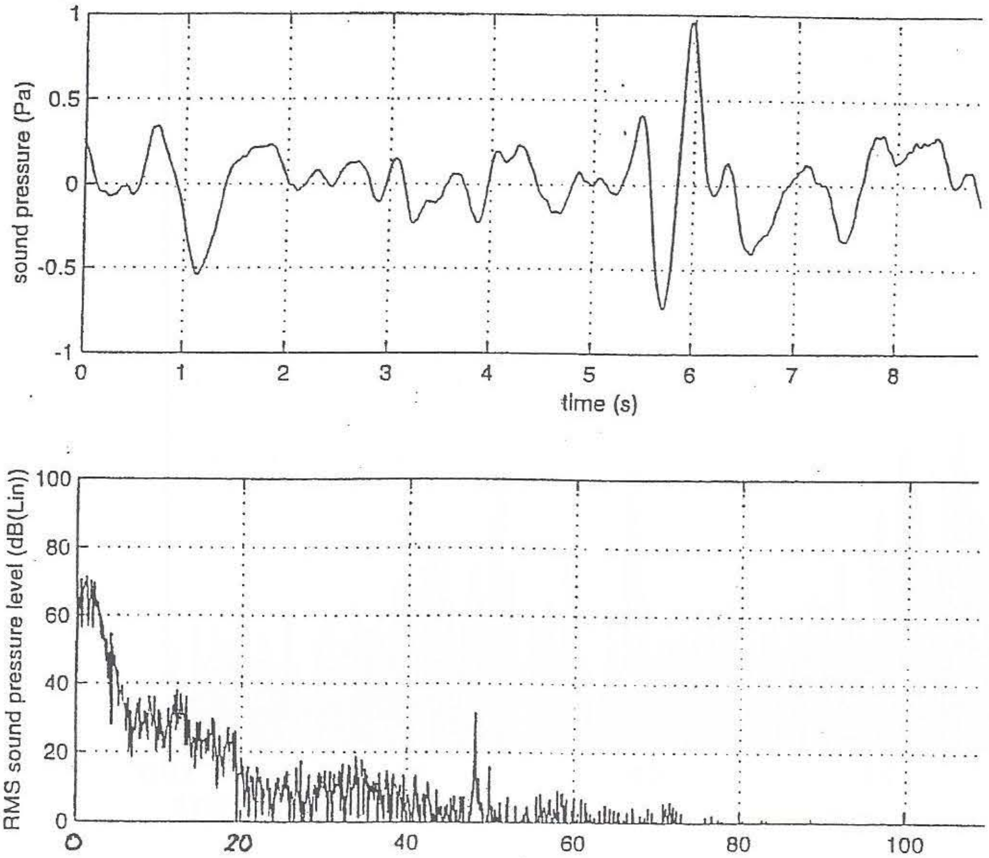


Fig 2 200 metres from LF noise B & K 2231 FFT analysis
Readings from Caravan Site

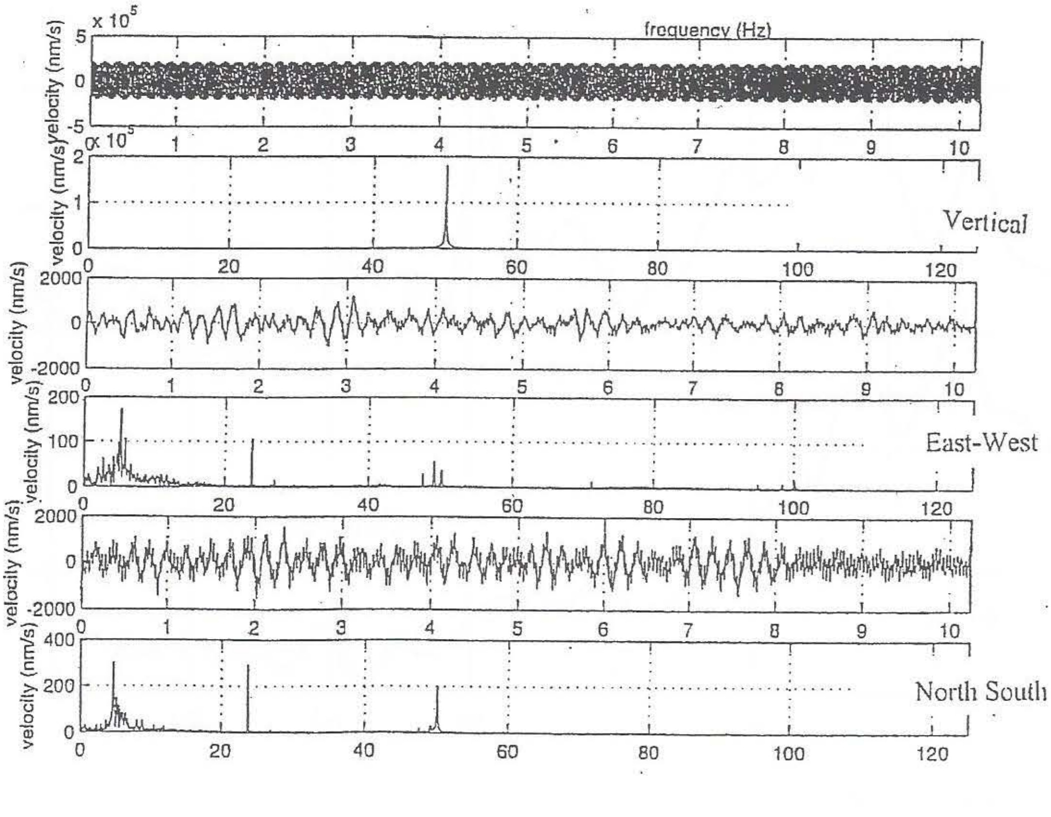


Fig 3 Lennartz Seismometer University of Liverpool

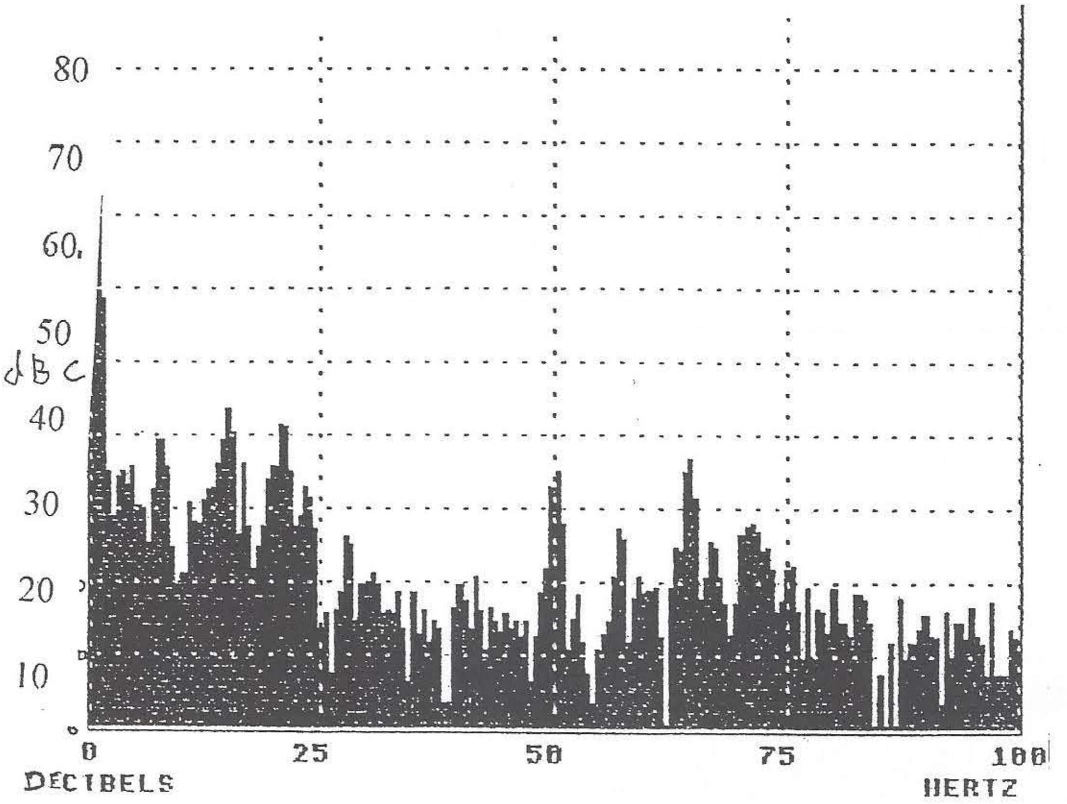


Fig 4 0.55 Hertz FFT analyser LF noise in Sufferers House

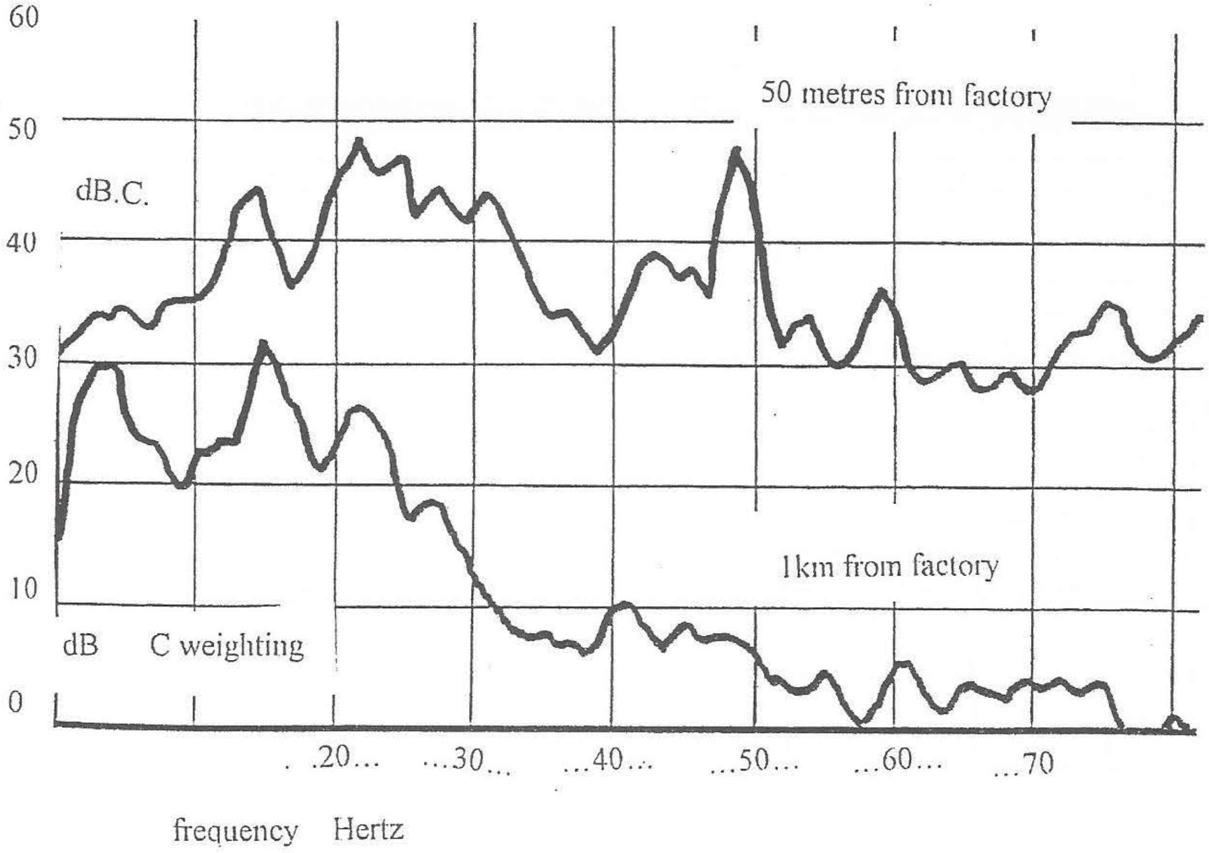


Fig 5 Average of 32 Readings Airborne LF noise from factory

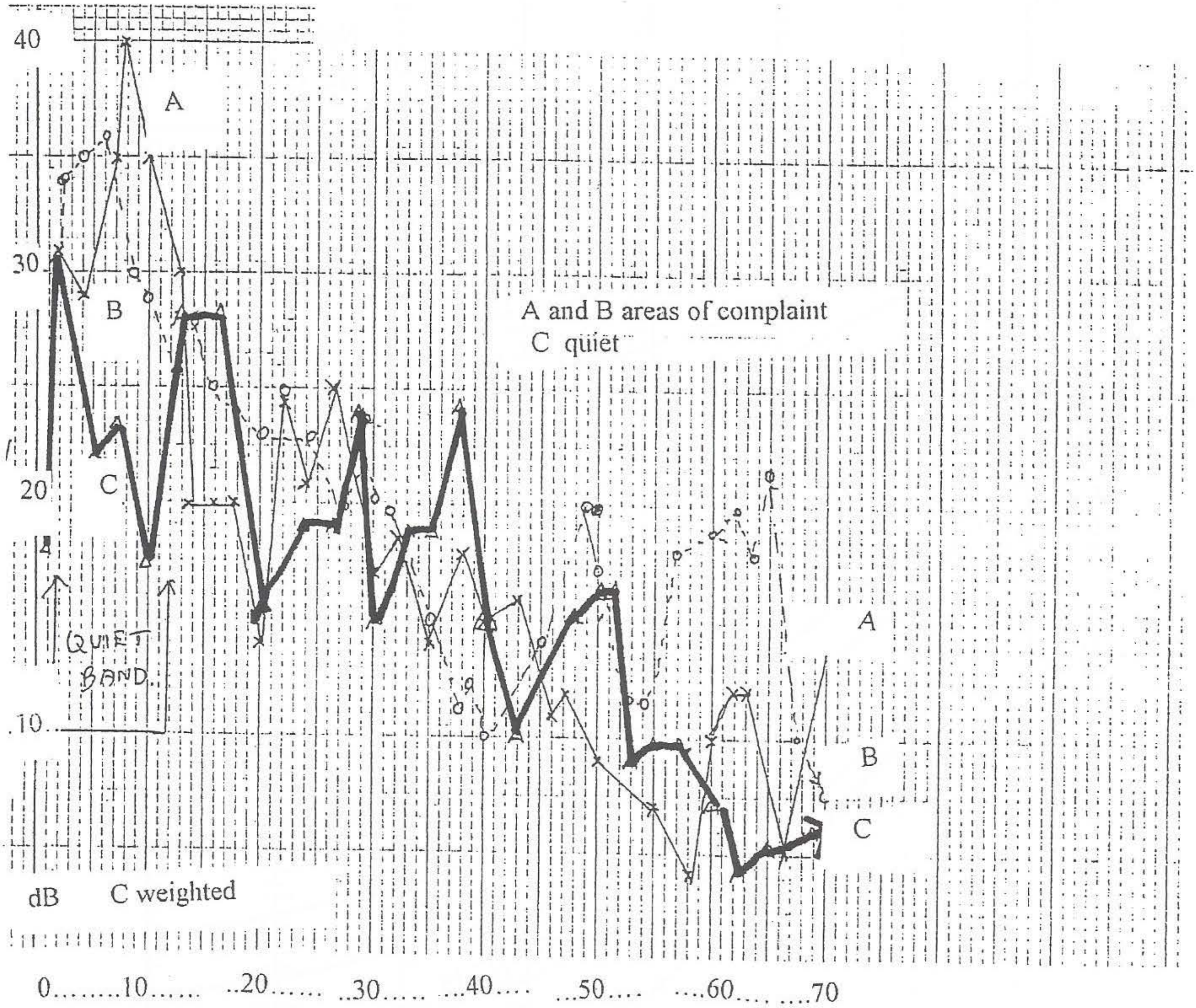


Fig 6 Spectra from Shropshire Noisy and Quiet areas

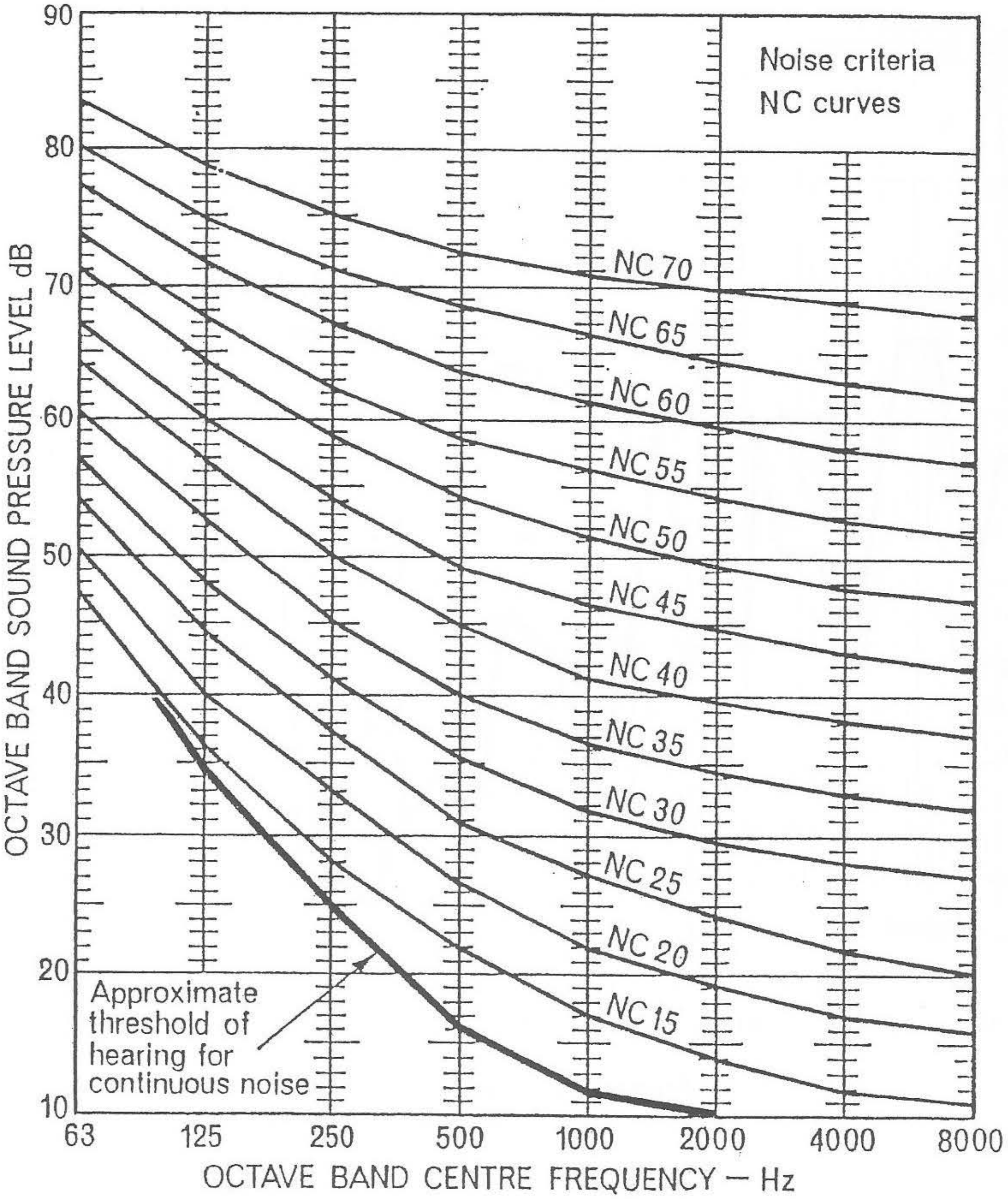


Fig 7 Equal Loudness Curves from Woods Practical Guide to Noise Control

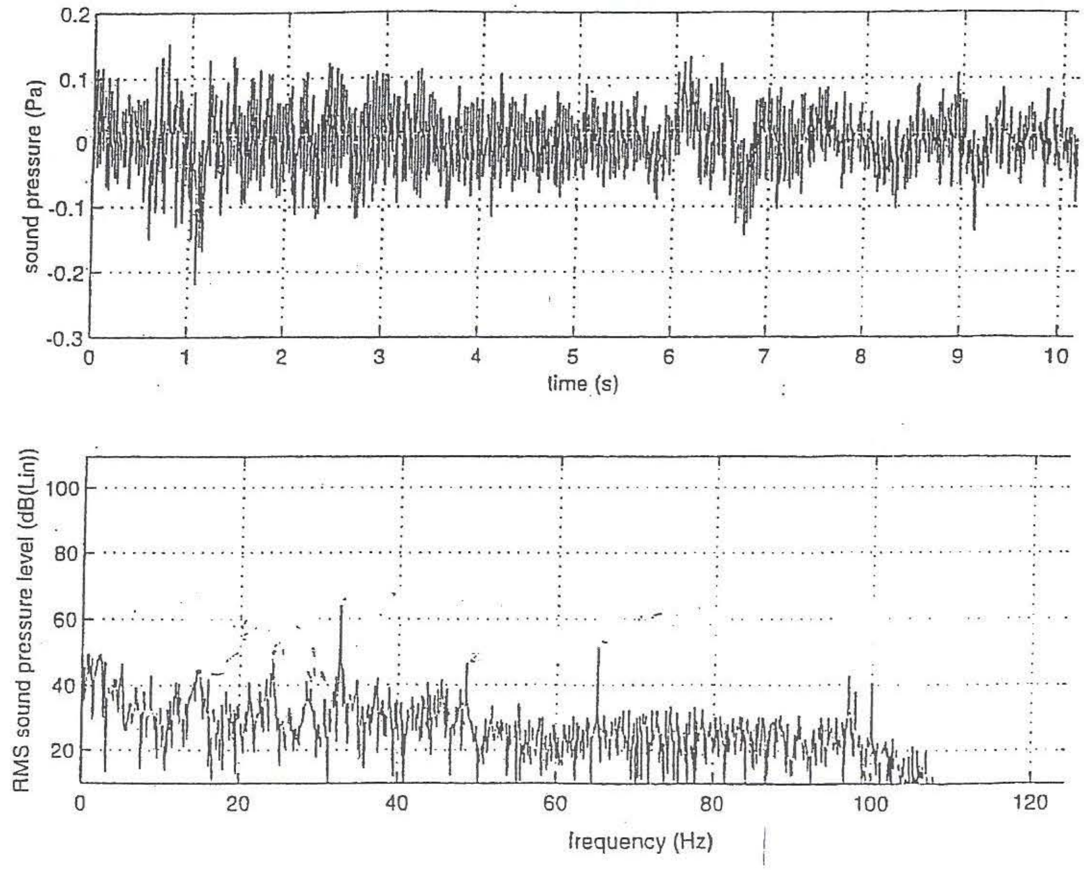


Fig 8 Liverpool Cathedral Tests

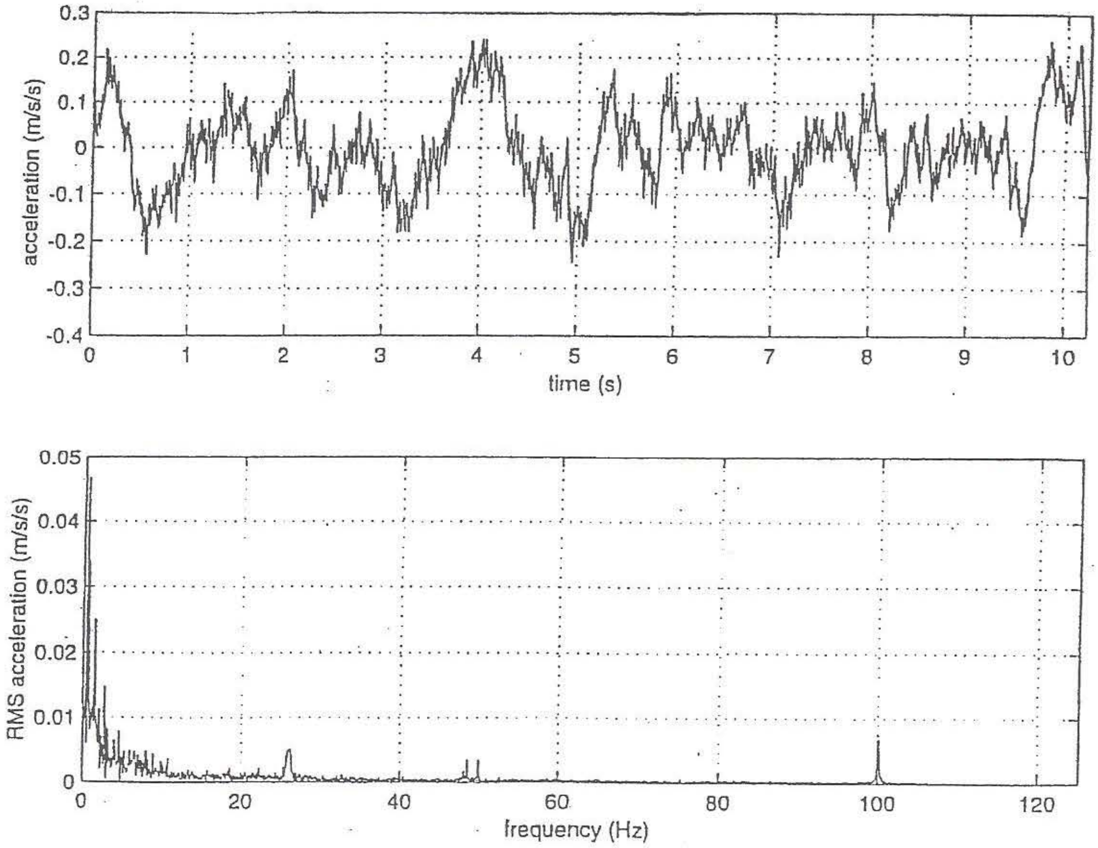


Fig 9 Accelerometer on window Noisy area

Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Evaluation of Low-Frequency Noise in Dwellings. New Polish Recommendations.

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Summary

The paper presents the new Polish recommendations for estimation of low-frequency noise (LFN) penetrating into dwellings from appliances installed inside or outside the building (Recommendation No 258/98 of Building Research Institute).

The new assessment criteria were proposed based on the measurement data of annoying noise, investigation of the noise effect on the health of exposed inhabitants, laboratory tests of thresholds of narrow- and broad-band noise perception, a review of the present literature. In order to assess the noise spectra measured in dwellings, the A10 characteristics as the rating curve has been accepted. Its L levels for one-third-octave bands are determined by relation $L_{A10}=10-k_A$.

The low-frequency noise occurs as annoying when the sound pressure levels of noise exceed the A10 curve and they simultaneously exceed the background noise level by more then 10 dB for tonal noise and 6 dB for broadband noise.

Introduction

Results of many tests indicate that a low-frequency noise (LFN) penetrating into dwellings is more difficult to tolerate and is perceived as more annoying than other noise. Moreover, commonly used methods of noise assessment by use of the single-number index such as the A-weighted sound level are unsatisfactory and they do not correspond to the subjective evaluation of the low-frequency noise. That is why many countries[7,8,10] have introduced the separate criteria relative to the low-frequency noise assessment.

Also in Poland there has been recently realized the study on the new criteria for evaluation of the low-frequency noise penetrating into dwellings. The final result of the investigation is the Building Research Institute Instruction No 358/98 entitled „Assessment of the low-frequency noise in dwellings”[6].The instruction comprises methods and criteria for evaluation of the annoyance of the low-frequency noise coming into the flats from appliances installed in a residential building or in its vicinity.

The paper further describes significant results of the tests performed as well as the general principles and the criteria of noise assessment presented in the above-mentioned Instruction.

Foundations of determination of the levels limiting the LFN

A programme of the study on determination of the levels limiting the LFN contained:

- identification of the main sources of annoying noise in residential buildings,
- noise measurements in flats and the objective and subjective evaluation of noise nuisance,
- medical inquiries about the effect of the long-lasting low-frequency noise on the human health,
- determination, under laboratory conditions, of the threshold values for the low-frequency noise perception in silence and in the presence of masking noise which approximates the background noise in flats in the daytime.

The results of the tests were discussed in publications[1-5]. The significant conclusions from the tests are as follows:

Measurement results. It results from the analysis of complaints about noise in dwellings that most of them concerns the noise coming from appliances like pumps, transformers, fans, refrigerator units installed inside or outside the building. The measurement results[1,4] have confirmed that the noise of these sources was the LFN containing components even in the range of 16 Hz. It was not observed the regular noise with infrasound components of significant levels in flats investigated. At the same time it was stated that in many cases the noise at very low levels to be generally regarded as acceptable, was subject of complaints. So, in order to develop the new criteria for the assessment of the LFN and define its acceptable levels, it was performed the epidemiological investigation among dwellers exposed to the LFN in residential environment.

Results of epidemiological investigation. The aim of the study was to evaluate subjectively the noise and determine if a long-lasting exposure to the LFN at low levels is potentially decisive of the health risk for the dwellers.

The investigation was performed by the Department of Epidemiology of the Medical Academy in Warsaw[2]. A method of the questionnaire investigation (inquiries) was applied to evaluate the state of health and subjective noise nuisance. The tests referred to adults (over 18) living in dwellings where occurred the LFN from appliances installed in the building and at least one person from that flat complained about the noise nuisance (group tested, designated Group T). By means of the matching method each individual of the Group T was matched with a person of the same gender, at the similar age, living in the same block of flats in a dwelling with a comparable level of background noise but without the LFN (control group, designated Group C).

In spite relatively small group of the individuals examined (about 60 persons) it explicitly results from the investigation that:

1. LFN even at levels approximating the detection thresholds and not exceeding the acceptable values of A-weighted sound levels is perceived as annoying or very annoying and creates the potential health hazard for the dwellers.
2. Among the individuals exposed to LFN there were stated the following symptoms to testify a worse state of health:
   - they more often defined their state of health as bad,
   - they really more often declared the heart ailments
   - chronic insomnia more frequently occurred at them.
3. Objective psychological tests among the individuals exposed to LFN revealed:
   - occurrence of features predistinating towards the so-called A type i.e. increased risk of heart infarct (Wrzesiñski's test to examine a complex of behaviours and attitudes),

- essential reduction in mood which may be both a cause and a result of sickness process (Beck's test to measure the state of possible depression).

4. The exposure to low-frequency noise may create the depression states or intensify a degree of depression already existing but of which the person is unaware (the moderately serious and serious depression occurred among some individuals exposed to LFN).

Results of laboratory tests on detection thresholds of the LFN

It has resulted from the LFN measurements and the public opinion poll that the LFN in flats may be annoying and may create a potential health risk for dwellers even though the sound pressure levels, in low-frequency bands, are in the proximity of detection thresholds and slightly exceed the background noise. As a subjective criterion of noise annoyance assessment it was assumed that the intolerable noise is annoying even though it is barely audible or just perceptible in the room.

In order to objectify this criterion it was necessary to determine the values of the SPL for which the LFN will be audible (perceptible) in residential rooms with average background noise. So, the next research stage, leading to the development of new assessment criteria and a determination of permissible levels of the LFN in flats, was the laboratory investigation of detection thresholds of the LFN.

The aim of investigation was to determine:

- a difference between the detection thresholds of the LFN and tonal signals (given in literature - among others ISO 226),
- whether the noise may be audible if the sound pressure levels of their tonal components are below the detection thresholds,
- when the LFN is audible against a background noise and how many decibels the SPL of tonal components of noise should be above the background noise in order to distinguish the noise from background.

Laboratory tests were performed in acoustically inactive chamber of the Musical Academy in Warsaw^3. There were determined the detection thresholds of tonal signals and 5 low-frequency multitones with components in the range of 20 - 200 Hz in silence and in the presence of the masker (broad-band noise with a spectrum approximating the background noise in flats in the daytime). It was used the 2AFC method. Figures 1-4 present the selected results of the experimental study obtained for 4 auditors.

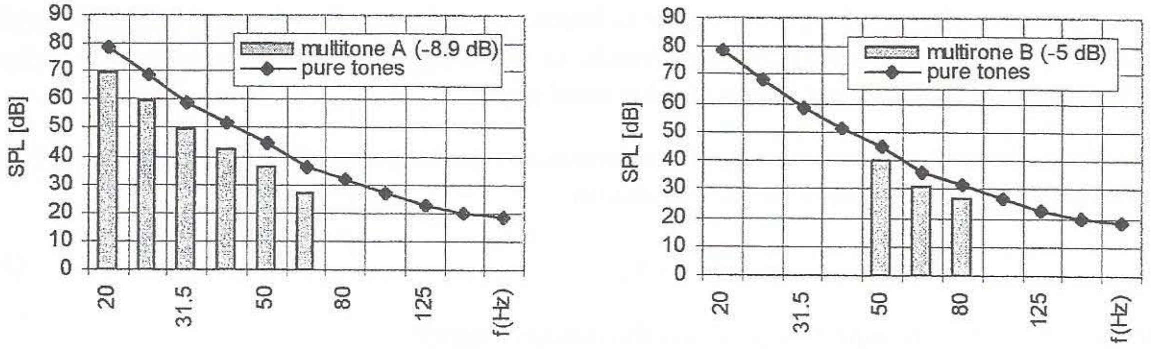

Fig. 1. Comparison between the detection thresholds for tonal signals and multitone A and B in silence.

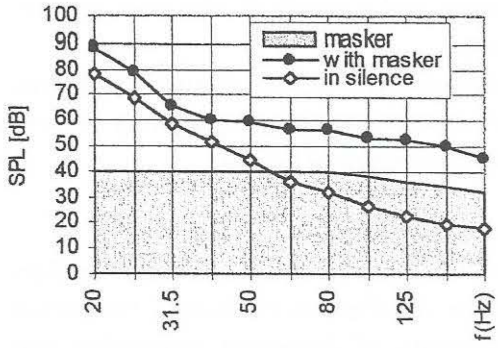

Fig.2. Comparison of levels of the detection thresholds for tonal signals in silence and in the presence of masker

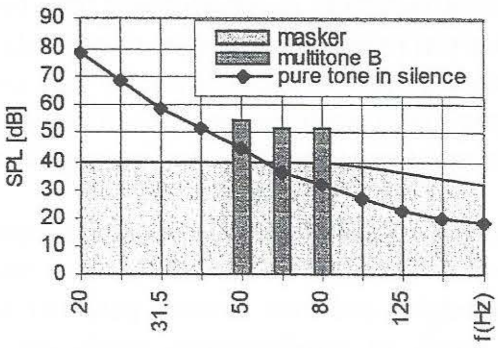

Fig.3. Levels of the detection thresholds for multitone B in the presence of masker.

The following conclusions stem from the analysis of investigation results:

1. Noise of multitonal nature may be audible even though the sound pressure levels of particular tonal components are below the detection thresholds. (Fig. 1). Even noises with tonal components lower by 10 dB than the threshold of hearing may be audible.
2. The more low-frequency components in noise the more a decrease in its detection threshold.
3. In the presence of masking sounds, the LFN of tonal nature is audible when the SPL of particular tones is about 12-16 dB above the SPL of masking sounds (Fig. 2)
4. Noise comprising more tonal components is audible when the SPL of tonal components is 7-11 dB above the SPL of masking sounds. Also in this case, the more tonal components in low-frequency range, the lower the levels of its detection (Fig.3).

The results of the above investigation as well as known from literature test results of the detection thresholds for infrasound (Watanabe and Moller[9]), and the permissible values of the LFN accepted in other countries: Germany[10], Sweden[7], Holland[8], as well as the accessible measuring equipment were the basis for determination of levels limiting the LFN in residential rooms.

A fundamental criterion for the low-frequency noise evaluation

The evaluation of the low-frequency noise is based upon the results of sound pressure levels measurement made in one-third-octave bands in the range 10-250 Hz during the source operation and when it is out of action (background noise).

To evaluate the noise it was accepted the characteristics, corrected with the A-weighting, determined in one-third-octave bands by relation:

$$L_{A10} = 10 - k_A \tag{1}$$

where: L_{A10} - sound pressure levels in one-third-octave bands,
k_A - values of the A-weightings for centre frequencies of one-third-octave bands.

This characteristics defines the limit of the recommended (safe) levels. It is denoted the A10 and corresponds to a curve of equal, corrected sound pressure levels L_{Af} = 10 dB. It means that in practice it can be evaluated the A-weighted sound pressure level in one-third octave bands.

Figure 4 shows the comparison of the A10 characteristics proposed by Poland with the curves representing the permissible (recommended) sound pressure levels at the low-frequency noise inside dwellings, suggested by other countries.

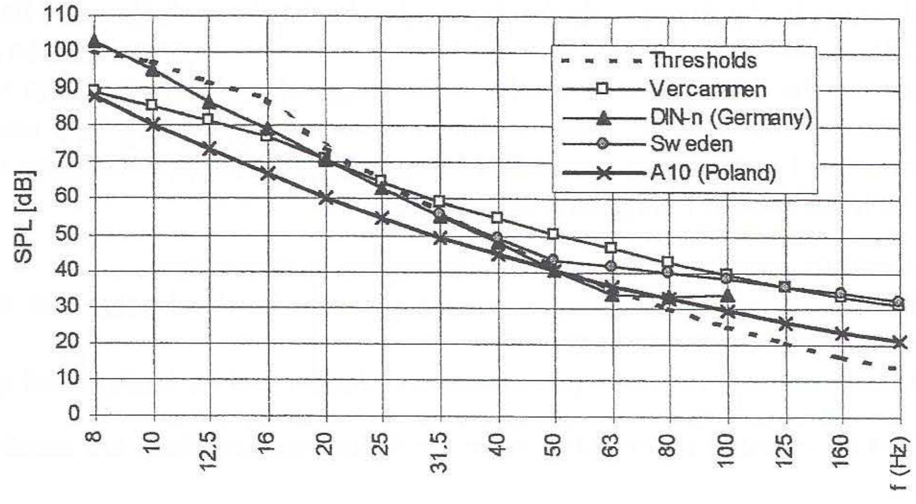

Fig.4. Permissible (recommended) SPL of low frequency noise inside dwellings proposed in different countries.

The characteristics described by the relation (1) satisfies the following conditions:

1. the sound pressure levels at values lower than the values determined by this curve seem, in the light of the tests, not to be danger for living environment and those at higher values may be already regarded as annoying;
2. the sound pressure levels determined by the A10 curve correspond to rather comfortable acoustical conditions in dwellings. Average levels of background noise at night for frequencies above 50 Hz are comparable with or lower than the levels determined by this curve. For lower frequencies they lie below this characteristics;
3. this characteristics in the frequency range above 80 Hz is similar to the isophonic curve of 10 phons, and it lies below the threshold curve for frequencies under 63 Hz;
4. for spectrum whose all components in the range of infrasound frequencies (above 10 Hz) would lie on the A10 curve, the infrasound level $L_G \approx 83$ dB;
5. for spectrum whose all components in the range of audible frequencies (20 - 20000 Hz) would lie on the A10 curve, the low-frequency noise index $L_{FA} \approx 21$ dB and the A-weighted sound level $L_A \approx 25$ dB;
6. the A10 characteristics corresponds to the curve of equal corrected sound pressure levels $L_{Af} = 10$ dB. It means in practice that the A-weighted sound pressure level in one-third octave band is a subject to evaluation;
7. the A-weighting characteristics is commonly known, so in many analyzers it is possible to read-out the spectrum corrected by the A-weighting. It makes possible to carry out the rough assessment of the low-frequency noise hazard under conditions of field measurements.

It can be seen that the sound pressure levels, determined by the A10 curve, lie below the perception thresholds for frequencies below 50 Hz and they are the lowest among the proposed ones but it is known that the detection for pure sinusoidal signals differs from that for pulsating noise or broadband noise where many spectrum components occur. (The thresholds for multiple tones detection, established in laboratory conditions, were even by 10 dB lower than those for pure tones detection.)

However, the A10 characteristics is not a sufficient criterion for noise assessment. The levels of the low-frequency noise detection also depend on the background noise level (masking noise). At night, the background noise levels in the range of low frequencies are usually below the A10 curve. In the daytime, the background noise levels are higher and lie between the A10 and A20 curves. So, in practice the sound pressure levels are greater for the annoying noise than those for the A10 curve, especially in the range of higher frequencies where the background noise level is greater. That is why it is necessary to take into account the background noise level in the noise assessment or actually the difference between the sound pressure level of noise and the background noise level.

In order to estimate the low-frequency noise it is necessary to determine:

- ΔL_1 - difference between the measured sound pressure level of noise and the sound pressure level determined by the A10 curve,
- ΔL_2 - difference between the sound pressure levels of noise and the background noise.

The noise should be regarded as annoying when the following conditions are simultaneously satisfied:

- $\Delta L_1 > 0$
- $\Delta L_2 > 10$ dB for tonal noise or $\Delta L_2 > 6$ dB for broadband noise.

Principles of low-frequency noise assessment

It is recommended to make the two-stage assessment of low-frequency noise:

- preliminary evaluation (graphic assessment),
- appropriate evaluation (complete assessment).

The preliminary evaluation enables to select a spectrum of the loudest noise among the spectra measured at the particular points in a room and it allows to determine:

- if there is a low-frequency noise in the room under examination,
- if it is advisable to perform the complete assessment.

The complete assessment is performed when the preliminary evaluation indicates the occurrence of the low-frequency noise in a room. Realizing the complete assessment it is also taken into account the difference between the values of a sound pressure levels of noise and background. The assessment is of computational character. It allows to determine the numerical values by which is exceeded the limit of the recommended levels as well as the background noise level and to state if the low-frequency noise to be occurred in a room is qualified as annoying.

Preliminary (graphic) evaluation. The preliminary evaluation is carried out graphically, by putting together a noise spectrum (sound pressure levels in one-third octave bands) and the A10 curve of the recommended levels. If there are noise components in the frequency range 10 - 250 Hz at the levels above those determined by the A10 curve, then it may be stated that a low-frequency noise occurs in a room. So, it is necessary to carry out the complete assessment.

By means of the A10 curve a noise spectrum may be evaluated in the wider range of frequencies (above 250 Hz). It can then be roughly found the frequency range where the loudest components of noise spectrum exist.

The graphic assessment may be also carried out in field conditions when the measurements are made with a real-time analyzer equipped with the A-weighting filter for noise spectrum.

In order to attain it, the A-weighted sound pressure levels have to be determined. If there are components (in one-third octave bands in the range 10 - 250 Hz) whose corrected sound pressure levels exceed the A10 curve then it is presumed the occurrence of low-frequency noise in a room (especially at night) and it is necessary to make an appropriate noise evaluation (complete assessment).

Figures 5 and 6 illustrate an example of the graphic assessment of noise spectra. They present spectra of transformer noise and background noise measured inside a flat at night.

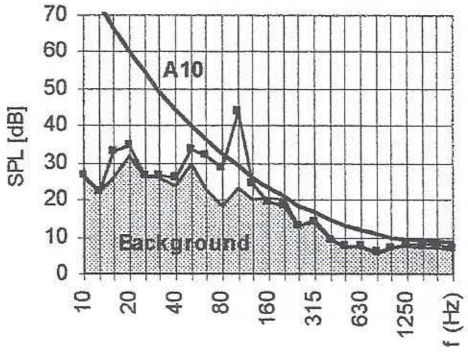

Fig.5. An example of graphic assessment of noise. A comparison between spectra of transformer noise, background and the A10 curve determining the limit of safe levels.

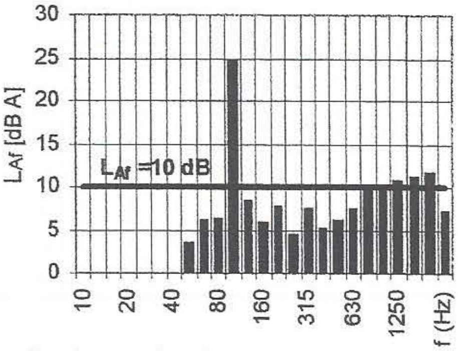

Fig.6. The A-weighted spectrum of the noise shown in Fig.5. An example of the preliminary visual evaluation of low-frequency noise by means of the real-time analyser.

As may be seen, there are noise components exceeding the A10 curve in the range of low frequencies. It means that the low-frequency tonal noise occurs in a room and it is necessary to carry out the complete assessment of this noise.

Complete assessment of low-frequency noise. The complete assessment of low-frequency noise consists in the evaluation of the following differences:

- $\Delta L_1 = L_H - L_{A10}$ - difference between the appointed sound pressure level in one-third-octave bands for noise (L_H) and the appropriate sound pressure level for the A10 rating curve determined by formula (1)
- $\Delta L_2 = L_H - L_T$ - difference between the sound pressure level for noise (L_H) and the background noise level (L_T).

It is necessary to calculate the above differences for all one-third-octave bands in the low-frequency range from 10 Hz to 250 Hz).

Table 1 presents an example of the complete assessment of noise. There are compared the spectra of transformer noise (L_H) and background noise (L_T) which were measured in a dwelling (see Fig. 5-6). It then shows the calculated ΔL_1 differences between the sound pressure levels of noise and the A10 curve as well as the ΔL_2 differences between the sound pressure levels of noise and background.
As can be seen in Table 1 this is a tonal noise with one component of 100 Hz at the level exceeding both the A10 curve and background noise by 14.7 dB and 20.4 dB, respectively. So, it results from this that the annoying low-frequency noise occurs in a room.

Table 1. An example of the complete assessment of low-frequency noise

Frequency, Hz	L_T	L_H	L_{A10}	ΔL_1	ΔL_2
10	26.0	26.4	80.4	-54.0	0.4
12.5	22.1	22.2	73.4	-51.2	0.1
16	26.0	33.3	66.7	-33.4	7.3
20	32.0	34.7	60.5	-25.8	2.7
25	26.0	26.6	54.7	-28.1	0.6
31.5	26.0	26.4	49.3	-22.9	0.4
40	24.0	25.9	44.6	-18.7	1.9
50	29.6	33.6	40.2	-6.8	4.0
63	23.0	32.2	36.2	-4.0	9.2
80	18.5	28.7	32.5	-3.8	10.2
100	**23.4**	**43.8**	**29.1**	**+14.7**	**20.4**
125	20.2	24.6	26.1	-1.5	4.4
160	20.5	19.3	23.4	-4.1	-1.3
200	20.2	18.6	20.9	-2.3	-1.6
250	13.0	12.9	18.6	-5.7	-0.1

Conclusions

The mentioned in the Instruction values, limiting the levels of the low-frequency noise, were accepted based on the results of the own study as well as the test results of the outstanding world laboratories (especially with reference to infrasound range). In the light of these tests the presented values seem to ensure rather comfortable acoustical conditions in flats and do nor constitute a potential health risk. Developing the assessment criteria the efforts were made to take into account the technical specifications of the measuring equipment and to adapt the criteria for performing the preliminary evaluation of the low-frequency noise hazard under the field conditions.

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Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Annoyance of low frequency noise and traffic noise

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Summary

The annoyance of different low frequency noise sources was determined and compared to the annoyance from traffic noise. Twenty-two test subjects participated in laboratory listening tests. The sounds were presented by loudspeakers in a listening room and the spectra of the low frequency noises were dominated by the frequency range 10 Hz to 200 Hz. Pure tone hearing thresholds down to 31 Hz were also measured. Eighteen normal hearing subjects and four subjects with special low-frequency problems participated in the tests.

Introduction

Complaints against low frequency noise sources in the environment have increased in recent years and in some cases the complaints cannot be verified by objective noise measurements. Typical low frequency noise sources are noise from power plants, noise from high-speed ferries, ventilating noise, etc.

In order to investigate the annoyance from low frequency noise sources and compare this annoyance to the annoyance from traffic noise, The Danish Environmental Protection Agency initiated the present investigation. At the time of writing the investigation is not finalized and the data presented here should thus be seen as preliminary results.

Listening tests

Listening tests were performed in a listening room where digitally recorded signals were presented over loudspeakers. The test subjects listened one at a time to eight different sound signals, each presented at three different levels. After each presentation a questionnaire was presented to the test subject. A written instruction was given to the subjects and the subjects could ask questions about the procedure throughout the tests. Information about the sound signals was only given after all the tests were finalized. A full training session was performed before the final tests were initiated.

Test signals. Seven low frequency test signals and one traffic noise signal were used: The low frequency signals were sounds from a gas turbine, a high speed ferry, a steel factory, a generator, a compressor, a drop forge (transmitted through the ground) and music from a discotheque. The traffic noise was a recording from a busy motorway. The signals were recorded on disk and filtered to simulate an indoor listening situation. The duration of all the signals was two minutes. The signals were presented at L_{Aeq} levels of 20 dB, 27.5 dB and 35 dB. The sound signals were presented in a random order and were presented twice to the test subjects.

Test subjects. Eighteen normal hearing test subjects participated. Pure tone audiometry was performed in the frequency range 125 Hz to 8000 Hz with a Madsen Midimate 602 audiometer equipped with Sennheiser HDA 200 earphones. The audiometer was calibrated according to the values given in Han and Poulsen (1998). Hearing threshold levels at or below 15 dB HL were accepted in the frequency range 125 Hz to 4 kHz and a hearing threshold level of 20 dB at a single frequency (incl. 8 kHz) was also accepted. Besides the normal hearing subjects, four test subject with special low frequency problems participated in the investigation. Pure tone audiometry for these subjects was also performed but no specific limits were set for these persons.

Listening room. The dimension of the listening room was 7.52 x 4.75 x 2.76 m's (L x W x H). The room fulfilled the recommendations given in IEC 268-13 (1983). A detailed description of the equipment and the presentation system may be found in Mortensen (1999). The sounds were reproduced by means of two KEF 105 loudspeakers and two Amadeus Sub subwoofers. The loudspeakers were hidden by a light curtain. The test subject was seated at a position where only one natural room-mode is dominant, i.e. a 45.5 Hz resonance. All signals were filtered to compensate for the resonance at this frequency.

The subject's task. After each presentation the subject filled in a questionnaire with four questions: 1) How loud is the sound? 2) How annoying is the sound if it should be heard at home during the day and in the evening? 3) How annoying is the sound if it should be heard at home during the night? Below each of these questions a horizontal line was given (length 10 cm, left end named 'not annoying', right end named 'very annoying') and the subject responded by making a mark on the line. The fourth question was 4) Is this noise annoying? and the response was given by a mark in either a 'yes' or a 'no' box.

Low frequency hearing thresholds. A determination of the pure tone hearing threshold was performed with a Two Alternative Forced Choice method with 800 ms sound signal durations. The procedure determines the 79.4% point of the psychometric function. A detailed description of the procedure may be found in Buus et al. (1997). The threshold was determined at 31 Hz, 50 Hz, 80 Hz and 125 Hz. A computer controlled Tucker Davis system with Sennheiser HDA 200 earphones was used for these threshold determinations.

Results and discussion

The result presented here are the raw average data and should be regarded as preliminary. No analysis has been performed yet. The average annoyance as a function of presentation level is shown in **Figure 1**. Each point represents the average annoyance from eighteen test subjects. The left panel shows the response from the question about the day and evening situation. The right panel shows the response from the question about the night situation. It is seen that the annoyance increases with increasing L_{Aeq} level. It is also seen that the annoyance generally is evaluated somewhat higher at night than during day-evening. It is also seen that the Drop Forge is the most annoying sound followed by Music and that these two sounds together with the Compressor may form one group during day/evening and the other sounds forms a less annoying group. A detailed statistical analysis will show whether this grouping can be confirmed.

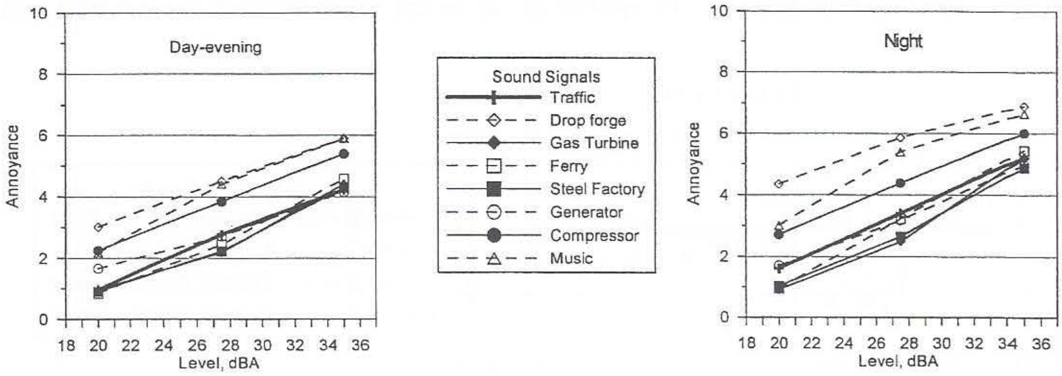

Figure 1 Perceived annoyance of seven different low frequency sounds. Each point represent the average over eighteen normal hearing subjects. Left panel: Annoyance during day and evening. Right panel: Annoyance during night. The annoyance is given as the position of the subjects' mark on the 10 cm questionaire line. Annoyance of traffic noise is represented by the heavy solid line.

In **Figure 2** the average annoyance perceived by the two subjects groups are shown for the day-evening and for the night situation. It is seen that the special group generally evaluates the sounds more annoying than the normal hearing group. This difference between the groups is more pronounced at night than during day/evening. At the time of writing a statistical analysis has not yet been performed.

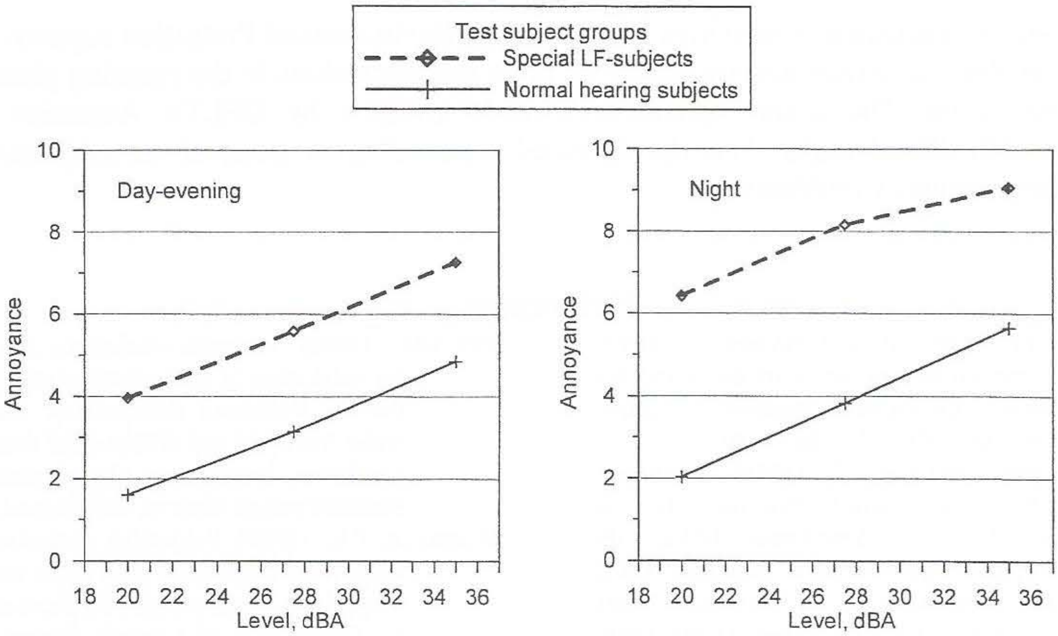

Figure 2 Comparison of annoyance perceived by eighteen normal hearing subjects and four subjects with special low frequency problems. Average over subjects and over all sound signals.

Hearing thresholds. The average audiogram (125 Hz to 8 kHz) is shown in **Figure 3** for both subject groups. It is seen that a high frequency hearing loss is found in the special group. The low frequency hearing threshold (31 Hz to 125 Hz) was measured for both subject groups, but as no audiometric calibration values exist in this frequency range, the measured values have been compared to the hearing threshold values given in ISO 389-7 (1996). This 'audiogram' (based on sound pressure levels) is also shown in **Figure 3**. It is seen that the low frequency hearing threshold for the special group is not better than for the normal group.

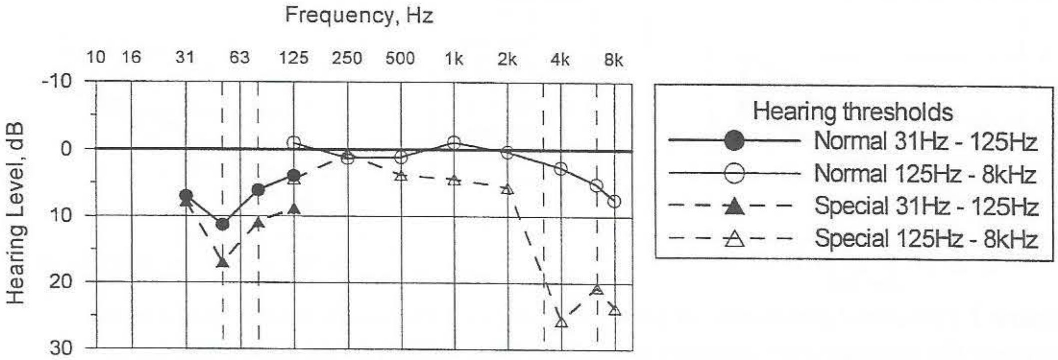

***Figure 3** Average pure tone threshold for the group af normal hearing subjects and for the group of subjects with special low frequency problems. The curves in the frequency range 125 Hz to 8 kHz is calculated from audiometric data. The curves in the frequency range 31 Hz to 125 Hz is based on measurements in dB SPL and referenced to ISO 389-7.*

Due to limitations in the equipment it was not possible to measure the hearing threshold at frequencies below 31 Hz. At the lower frequencies a hissing noise became audible at high presentation levels and this would result in erroneous results.

Acknowledgements

The present investigation is supported by The Danish Environmental Protection Agency. Mr. Jørgen Jakobsen is greatly acknowledged for ideas and discussions in the planning phase of the investigation. The sound signals were made available by DELTA Acoustics and Vibration, DK-2800 Lyngby. Tina Hjordt helped in providing the group of test subjects with special low frequency problems.

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Complaints of infrasound and low-frequency noise studied with questionnaires

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Summary

A survey of complaints about infrasound and low frequency noise has been carried out. 167 persons reported about their annoyance in a questionnaire. Their verbal reports often describe the sound as deep and humming or rumbling, like coming from a distant idling engine of a truck or pump. Nearly all respondents report of a sensory perception from the sound. In general they report that they perceive it with their ears, but many mention also a perception of vibrations, either in their body or of external objects. The sound disturbs and irritates during most activities, and many consider its mere presence as a torment to them. Many of the respondents report on secondary annoyance in terms of various kinds of unpleasantness (e.g. insomnia, headaches, palpitation), which they associate with the sound mainly because it occurs at the same places as the sound. In a majority of the cases, only a single or few persons can hear the sound, but there are also examples where it is claimed to be audible to everybody. Typically, measurements have shown that existing limits (and hearing thresholds) are not exceeded. The investigation leaves the key question: Is the annoyance induced by an external sound or not, and if it is, which frequencies and levels are then involved. The feasibility of a study of this is supported by the results.

Introduction

For many years there have occasionally been cases where people complain about infrasound or low frequency noise. This is the case in Denmark, and probably the situation is comparable in many other countries. Most descriptions mention a deep humming sound in the home of the complainant, which annoys and disturbs sleep, rest and concentration. In addition, the sound is often claimed to cause an impaired quality of life due to headache, pain, stress, and other kinds of unpleasantness, including severe worries of being exposed to a 'mysterious sound'.

Typically, the sound is only perceived by a single person and not the entire household. For this reason, among others, it is often proposed that it is doubtful to consider the problems as induced by an external, physical sound. As a consequence, in most cases no action is taken, and the complainant is left alone with his or her problem. Many of the annoyed persons find this situation unacceptable, and in Denmark some of these have organized themselves in a society, "Enemies of Infrasound" ("Infralydens fjender"). The society puts a constant pressure on the authorities by repeatedly bringing up their problem, e.g. in the press.

A disturbing matter is the widespread misunderstanding that infrasound is inaudible for humans, because the frequency components are placed below the *'audible frequency range'* from 20 Hz to 20 kHz. Although it was shown at least as early as in the 1930'es that infrasound can be perceived, when only the sound pressure level is sufficiently high ([1], [2], [3]), this misunderstanding still exists, even among professionals. As a consequence, the mere mention of the word *infrasound* brings up associations to 'inaudible sound', which is hardly worth to take seriously.

Official initiatives in Denmark. In 1995 the Danish Environmental Protection Agency arranged noise measurements in some selected cases. The measurements usually showed sound pressure levels well below or, at the highest, around the normal hearing threshold for low and infrasonic frequencies, a fact that added to the skepticism towards the complainants. The hypothesis was put forward that they might suffer from a special low frequency tinnitus, but this was never confirmed.

Also in 1995 the Danish National Board of Health took the initiative to form a group of general physicians, epidemiologists, audiologists and engineers to consider the situation. The group soon realized that the most urgent matter was to clarify, whether the annoyance was really induced by an external sound or not, and if it was, which frequencies and levels were involved.

The group planned a research program, which included a detailed investigation of 20 selected cases. The program would comprise sound measurements and calibrated recordings at the places of the claimed exposure. Each recording would subsequently be played back in the laboratory to the actual complainant, using a pattern of blind tests to see whether the sound could be heard and recognized. Also playback of filtered recordings was planned in order to encircle the frequencies responsible for the annoyance. The playback was planned to take place at Aalborg University, thus taking advantage of exposure facilities, which cover both the infrasonic and low frequency range. Furthermore, all complainants would have a general medical check and undergo detailed audiological and vestibular examinations, including examinations at low and infrasonic frequencies.

Unfortunately, due to disagreement about the financing between the National Board of Health and the Environmental Protection Agency, the proposed program was never accomplished. Soon after it had been given up, the Environmental Protection Agency issued an information report on low frequency noise, infrasound and vibrations [4]. The report recommends that the indoor noise in dwellings should not exceed 85 dB(G) for the infrasound and 20 dB(A) for the low frequency noise up to 160 Hz. For frequencies below 20 Hz these limits guarantee a sound pressure level approximately 10 dB lower than the average hearing threshold. Going towards higher frequencies, the limit passes the average threshold around 30 Hz (ISO 389-7 [5]), and a level 10 dB above the average threshold is reached around 70 Hz. These limits appear quite reasonable, provided that they are used with measurements that truly represent the human exposure. On the other hand, it seems that in most of the cases, which initiated the information report, measured levels are below these limits, and the report apparently stopped further examination of these cases.

(The information report [4] states that the limit is 10 dB below the average hearing threshold up to 40 Hz. This is not true; the 'average hearing threshold' used to show this is the average of a few investigations of which some are clearly doubtful in the 25-50 Hz range).

The present situation. It is a fact that our knowledge of low frequency hearing is based on a few investigations with a limited number of subjects, and it cannot be excluded that there are individuals with a much better or otherwise deviating hearing at these frequencies. If this is the case, it might not justify a lowering of the general limits, but a better understanding might lead to tools and solutions that could alleviate the annoyance in specific cases. It is characteristic for many cases that the annoyed person, or even an alleged 'noise polluter', is not unwilling to pay for a solution, if he or she only knew what to do.

It is no secret that the authors of the present paper find it unsatisfactory that the investigation proposed by the National Board of Health group was given up. We are well aware that the investigation might show that the annoyance is induced by physical sound in only few or even none of the cases. Even that would be a valuable result, though, since it would pave the way for a constructive search for other possible reasons. The uncertainty which is still connected to the matter has irrational consequences, e.g. power plants and factories being accused of 'polluting' entire regions with noise, worries about effects of sound based on pure speculation, worries that house prices will go down in 'polluted' areas etc. There are even examples of local authorities who have abstained from investigating straightforward cases of noise complaints with reference to these problems.

We have often been tempted to carry out the laboratory blind tests on our own expense. However, we have intentionally refrained from starting this, since we would only be able to examine a small group of complainants. We imagine that there may be a variety of reasons for the complaints, and there would be a high risk of making wrong conclusions from an insufficient investigation.

Present study. The survey presented in this paper is the result of a persistent pressure of 'at least doing something' from "Enemies of Infrasound", consulting acousticians, and some civic and regional authorities dealing with noise—as well as of our own curiosity. It has been the intention among other things to clarify, whether the annoyance experienced by different people is similar and what it is, whether there are reasons to believe that the annoyance is induced by physical noise or not, where and when the problems occur, whether problems occur all over the country, and what has been done to solve the problems. The present paper summarizes some important results of the survey.

Design and distribution of the questionnaire

The questionnaire was printed on nine sheets of A4 paper and included an instruction and 45 numbered questions. It was prepared in such a way that the annoyed person could fill it out directly, or a family member or case officer could do it, e.g. via an interview. The cover letter recommended that the annoyed person did it personally. Most of the questions were structured in a multiple-choice form. A few questions required text to be entered.

Instructions. The respondents were encouraged to add comments in the large margins of the sheets, if the multiple choice possibilities did not offer the relevant answer. It was pointed out that they were allowed to abstain from answering some of the questions, and that it was legal to give more than one answer in a question if appropriate. For these reasons the percentages of answers in a multiple-choice list will not necessarily sum up to 100%.

Depending on the situation and the answers given, some of the 45 questions would be irrelevant for some people. For this reason the respondents were sometimes told to skip questions and go to a subsequent question, depending on the answers already given. Some people were obviously too eager in answering the questions and did not make the correct jumps. These were kindly asked to fill out a new questionnaire, unless the error could be rectified in the data processing without any risk of misinterpretation.

Distribution. Questionnaires were sent to civic and regional environmental administrations throughout the country, to the secretariat of "Enemies of Infrasound" and to a number of acoustic consultants in Denmark. It was furthermore available in PDF-format from the internet homepage of the Department of Acoustics, Aalborg University. People were encouraged to copy and distribute it freely.

Because of the distribution form, it is not known how many copies that were actually distributed, and the responses cannot be used to estimate the number of annoyed persons, the geographical distribution of the problems, or any similar statistics. As an example of an odd distribution, clearly more responses were obtained in the region close to the secretariat of "Enemies of Infrasound" than from other regions. This might indicate more problems in this region, but more likely it demonstrates the society's success in using the press to make people aware of the survey (and of the problem). The responses must simply be taken as examples of cases where a person has a problem, which he or she believes is associated with low frequency noise or infrasound.

171 questionnaires were returned, most of these within the first months following the launch of the campaign in August 1998. 4 persons did not respond to a request of clarification in connection with incorrect jumps, thus leaving 167 responses for analysis.

Questions and Results

Almost all questionnaires were filled out by the annoyed person and only a few were filled out by family members or case officers. About two thirds of the respondents were female and one third was male. The only well established evidence of women having a better hearing than men is at high frequencies, where the impairment of hearing with age differs between genders (ISO 7029:1984 [6]). Even though the similarity of hearing between genders has not been fully confirmed at very low frequencies, the difference in number of respondents is more likely caused by social or psycho-social reasons.

Questionnaires were received from all over the country. Large and small cities as well as the countryside were represented. The respondents were between 14 and 86 years of age with a mean of 55.6 years.

Individual's description of the sound. In the first question that was not just of a formal nature, the persons were asked to describe the sound in their own words, and eight blank lines were left for this purpose. Most of the respondents tried eagerly to give a detailed description of the sound. Naturally, there is a large variety in the answers but some expressions are frequently used, such as the sound....

....is a deep humming/rumbling sound,
....is constant and unpleasant,
....creates a pressure in the ears,
....affects the whole body,
....sounds like coming from a large (idle running) engine of a truck, pump, ferry or aircraft,
....is coming from somewhere far away, outdoor, and may be transmitted through the ground.

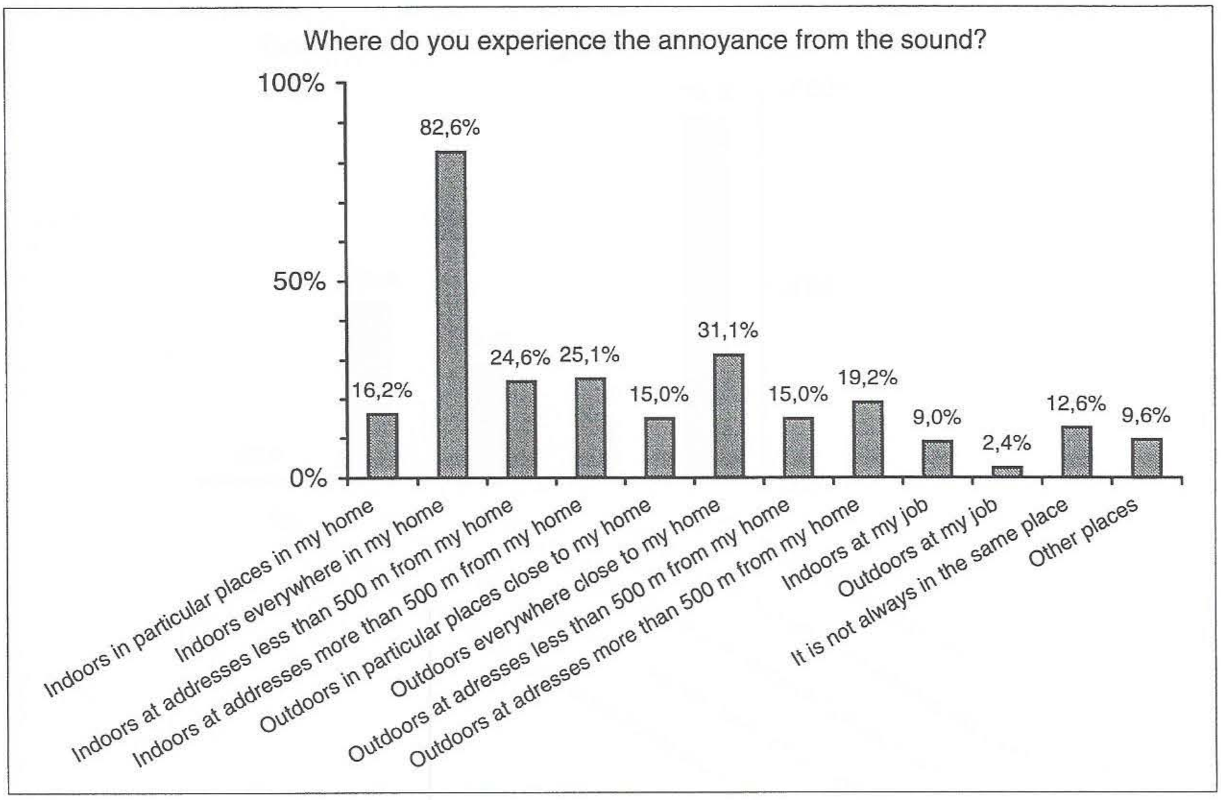

Figure 1. Question 6, places where the annoyance occurs. Rates of answers given in percentage of all respondents.

Many persons are apparently not able to localize the sound source directly. Therefore they make a number of speculations on what may be the source. The impression of the source being far away and outside the house may be caused by lack of midrange and high frequencies. Then our common experience from sound transmission through walls and over long distances could create the illusion of a distant source, even if the sound is actually generated nearby.

Where and when the annoyance occurs. In one question the persons were asked where they experience the annoyance. The responses in terms of statistical frequencies are shown in Figure 1. It is seen that nearly all of the persons are annoyed indoors in their home, either all over the home (82.6%) or at particular places (16.2%). Furthermore it is seen that the annoyance is experienced not only inside buildings, but also sometimes outside. Only few problems are seen at the job. Many people added margin comments on extra details like where in the home the sound is most intense, how their experience is at other places etc.

In another question the persons were asked which time of the day the annoyance occurs. The answers were almost equally distributed between day, evening and night, however with a small preponderance in the nighttime (22:00-7:00). A vast majority marked two or three of the three intervals.

Is the sound perceived with the senses? As mentioned, it has often been argued that some of the complainants might not actually *hear a sound*, but rather feel some general unpleasantness and put the blame on sound, only because of rumors about strange effects of infrasound and low frequency noise. In one question the persons were asked, whether they perceive the sound directly with their senses. In order not to bias the persons towards

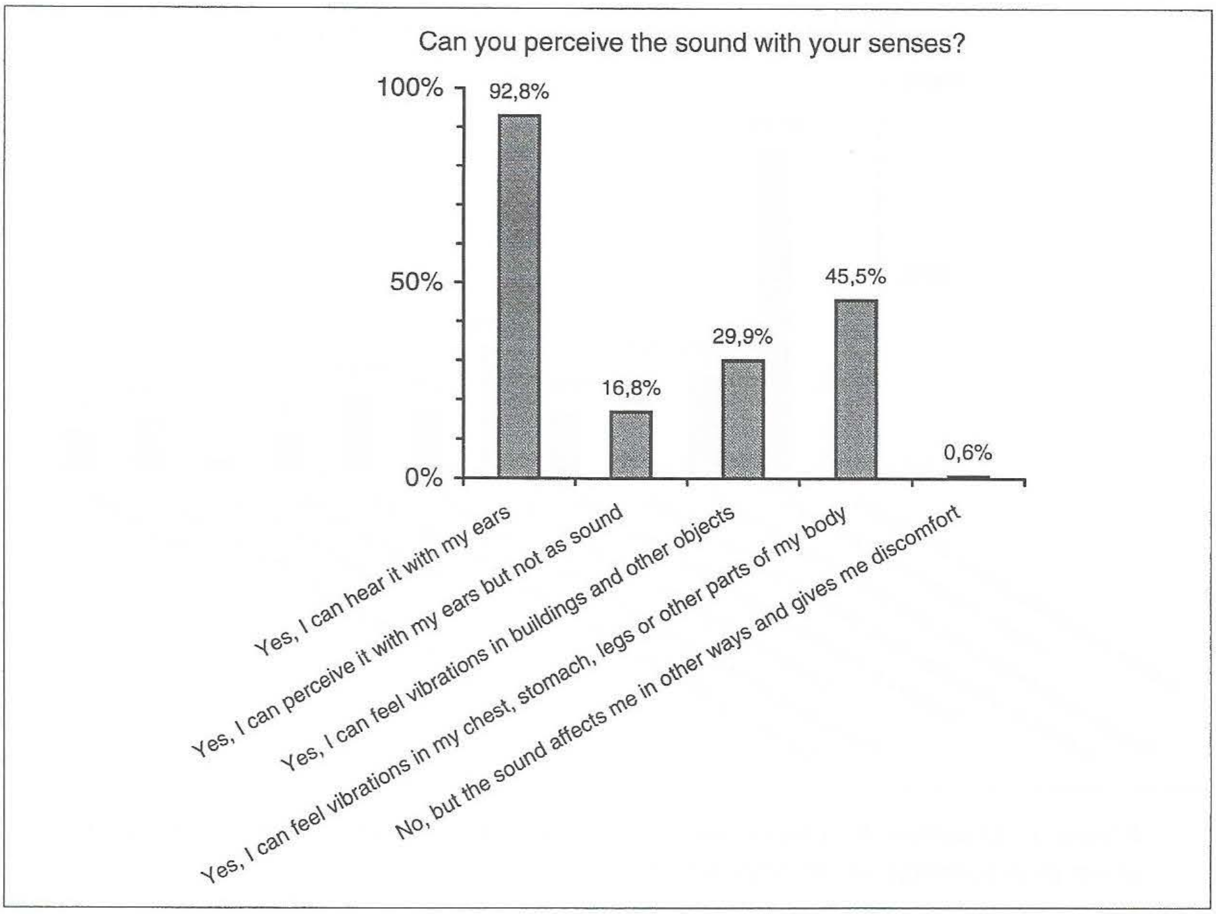

Figure 2. Question 7, sensory perception. Rates of answers given in percentage of all respondents.

reporting a false sensory perception, the wording of the question and the possible answers were carefully selected in order to make it perfectly 'legal' and not in any way doubtful to admit that the sound was not directly perceived.

The results of this question are given in Figure 2. It is seen that nearly all persons (92.8%) report that they hear a sound with their ears. Some persons (16.8%) report of a sensation in the ears apart from a sound. 97.6% answered one or both of the two first categories, thus nearly all respondents have a sensory perception related to the ears. Large parts of the persons have a sensation of vibrations, either in their body (45.5%) or of objects around them (29.9%).

Only 0.6% (a single person) did not report of a direct sensory perception. This person reported insomnia and headache, and as a reason for blaming infrasound or low frequency sound, the person reported that he or she had heard or read that it might be the reason.

In one question the persons were asked how long time they have to be in the sound before the annoyance occurs. Results from this question are given in Figure 3. Obviously, the annoyance starts very soon for most of the persons, as 64.7% indicate "immediately" and 23.4% state "within a few minutes" (a few persons reported both of these answers, thus 85.0% answered at least one of them). The immediate occurrence of the annoyance corresponds well with the direct sensory perception.

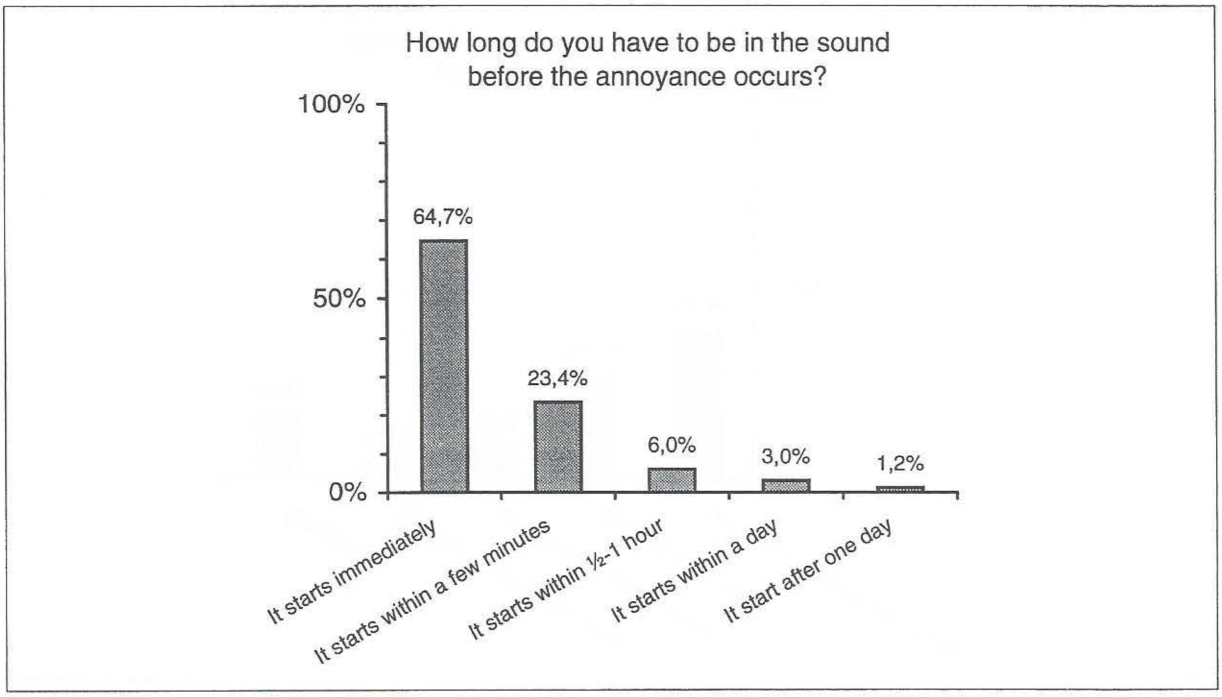

Figure 3. Question 28, time before annoyance occurs. Rates of answers given in percentage of all respondents.

Can other people hear the sound? The persons with a reported direct sensory perception were asked whether other people are able to perceive the sound as well. The results from this question are shown in Figure 4. 39.6% reported that he or she is the only person who can hear it, while 27.7% indicated that a few persons can hear it. Only 17.0% indicated that the sound is audible to everybody.

Some persons added extra information on exactly who can hear the sound, or mentioned that he or she lives alone and does not have visitors very often. In such cases there may be a bias in the answers, since more persons than indicated might be able to hear the sound, if only other people were being exposed to it.

In another question the persons were asked, whether other people had mentioned the sound without being made aware of it. This had happened in 39.0% of the cases.

Kinds of annoyance. The persons with a sensory perception were asked which kinds of annoyance that are related to the sound. The question was split up into primary annoyance, i.e. annoyance directly related to the perception, and secondary annoyance, i.e. other kinds of unpleasantness believed to be induced by the noise.

The answers from the question concerning primary annoyance are seen in Figure 5. A majority of the persons reported on problems like being disturbed when falling asleep or when reading, frequently paying attention to or being irritated by the sound, and being awakened from sleep. 78% consider the mere presence of the sound as a torment to them. An example from the "Others" category is pressure in the ears.

The answers concerning secondary annoyance are seen in Figure 6. The highest rates (around 70%) occur for insomnia and lack of concentration, unpleasantness which is nearly 'primary'

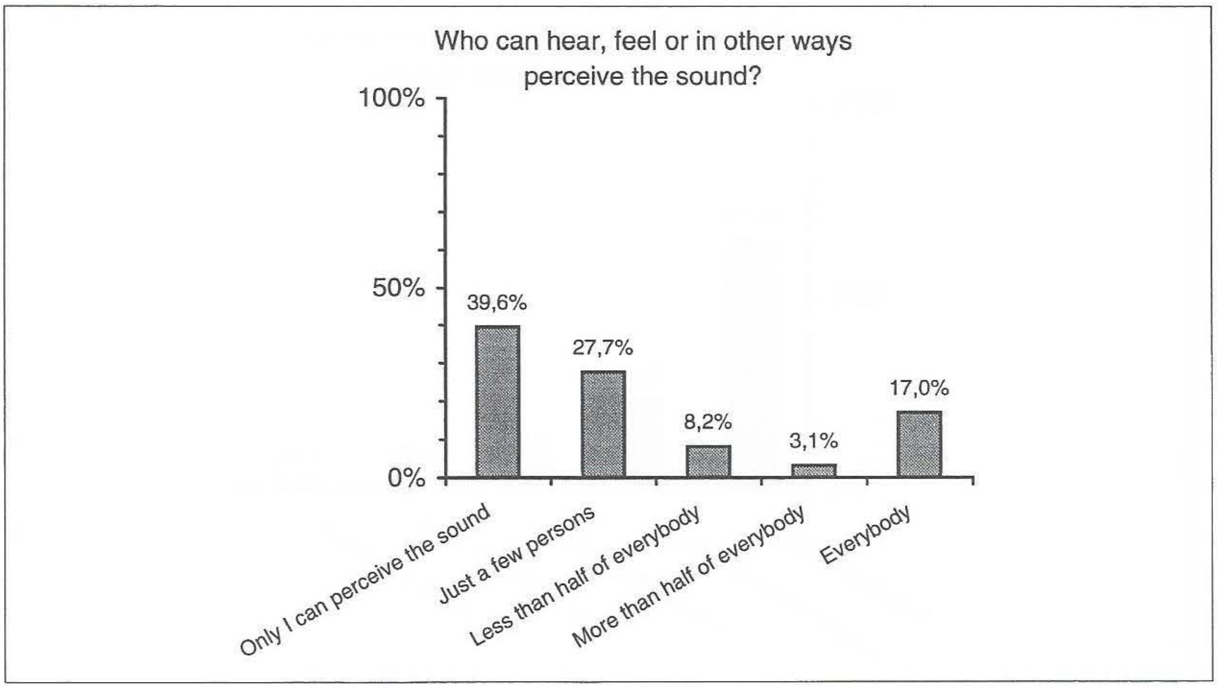

Figure 4. Question 14, number of persons who can perceive the sound. Rates of answers given in percentage of respondents with claimed sensory perception.

and which was more or less reported already in response to the question on primary annoyance. As examples of truly 'secondary' effects, large groups reported dizziness, headaches and palpitation. Examples from the "Others" category are stress, aggression, restlessness, nausea, fatigue, increased tension in muscles, and weak nerves.

Those persons who indicated secondary annoyance were asked why they believe infrasound or low frequency noise is responsible. 79.7% of them relate the secondary annoyance to the sound because it appears at the same places. Quite many (38.5%) indicate that they have heard or read that the unpleasantness may be induced by sound.

Attempts to improve the situation. In one question the persons were asked what they have done in order to relieve the annoyance. Quite many have tried to use earplugs at night (64.2%) or during the day (37.7%), most often without any effect. 9.4% have moved to another house, and 52.8% consider doing it. 42.8% have consulted their general practitioner or a specialist, and 17.6% take medicine.

Complaints to authorities. 64.2% of the responding persons have complained to the authorities about the noise. In 15.9% of these cases the complaint was rejected immediately. In 63.5% an official person has visited the complainant or an address in the neighborhood in order to evaluate the situation.

Noise measurements have been made in 49.5% of the cases in which an official complaint was filed, vibration measurements in 10.2%. Typically, measurements did not reveal anything that was expected to give rise to problems (or be audible), and existing limits were usually not exceeded. (This refers to the explanations given by the annoyed persons; the authors have not had the opportunity to study the original measurement reports). Measurement difficulties are frequently reported, e.g. because of background noise or insufficient equipment. Some of the persons have expressed their distrust in the measurements and the limits.

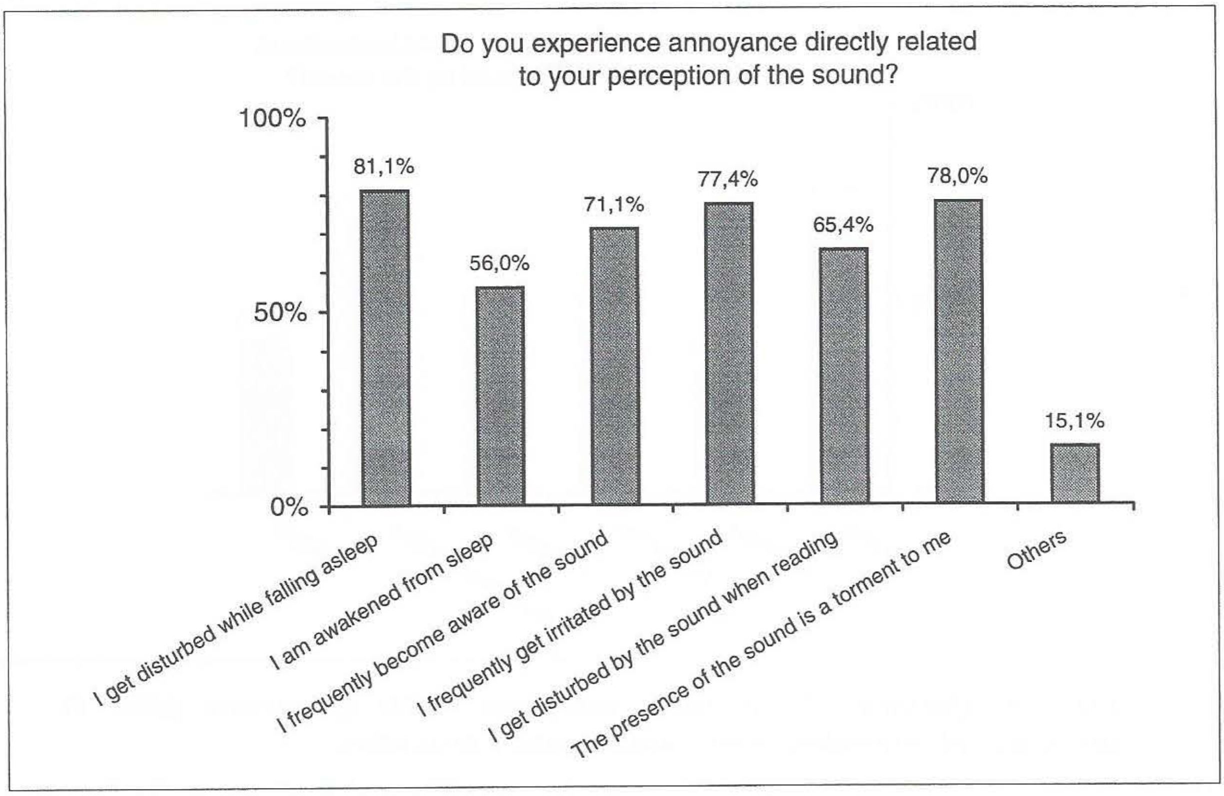

Figure 5. Question 16, primary annoyance. Rates of answers given in percentage of respondents with claimed sensory perception.

Only 8.4% of those who have complained to the authorities feel that their problem has been solved or partly solved. However, in an investigation like the present, there will be a natural bias towards a low number of persons for whom the problems have been solved, since these persons will be less motivated for filling out a questionnaire than those who still have a problem.

Conclusion

The 167 respondents experience the annoyance mainly in and around their homes. Their verbal reports often describe the sound as deep and humming or rumbling, like coming from a distant idling engine of a truck or pump. Nearly all respondents report of a sensory perception from the sound. In general they perceive it with their ears, but many have also a perception of vibrations, either in their body or of external objects. The sound disturbs and irritates during most activities, and many consider its mere presence as a torment to them. Many of the respondents report on secondary annoyance in terms of various kinds of unpleasantness (e.g. insomnia, headaches, palpitation), which they associate with the sound mainly because it occurs at the same places as the sound. In a majority of the cases, only a single or few persons can hear the sound, but there are also examples where it is claimed to be audible to everybody.

There are respondents from all over the country, however with a preponderance in the area where "Enemies of Infrasound" has been particularly active. There are more women than men among the respondents. Many of the respondents have complained to the authorities, but most often this has not led to a solution. Typically, measurements have shown that existing limits are not exceeded. Sometimes authorities have rejected cases immediately. The study is most

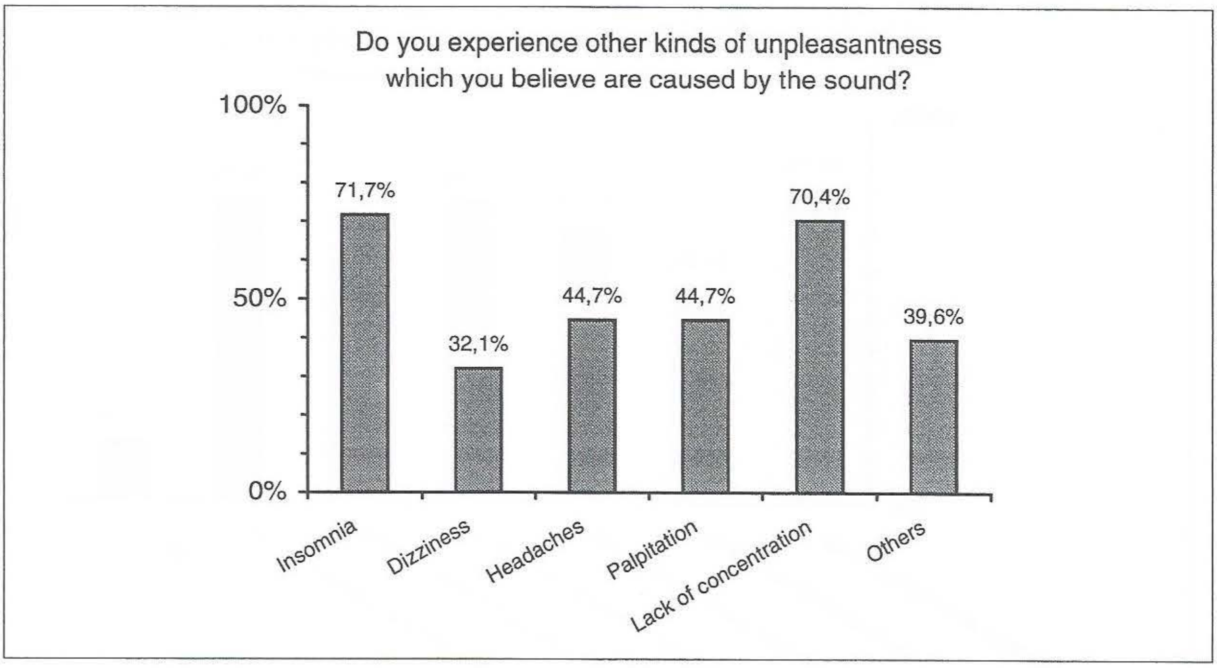

Figure 6. Question 17, secondary annoyance. Rates of answers given in percentage of respondents with claimed sensory perception.

likely biased towards having unsolved cases, since people with solved problems are less motivated towards submitting a questionnaire. Because of the simple distribution form of the questionnaire, the result of the investigation cannot be used to estimate the extent of low frequency problems in the country, but the cases must be regarded as examples only.

Even when the respondents report a sensory perception, this perception does not have to be induced by an external sound exposure. An investigation previously proposed by the National Board of Health group is needed more than ever as a means in clarifying whether external sound is responsible, and if so, which frequencies and levels are involved. The fact that most of the respondents report that the annoyance starts very soon after they are exposed, is further motivating, and it will facilitate the design of blind tests.

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Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Proposal of new limit values for occupational exposure to infrasonic noise in Poland

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Summary

The present paper describes the sources of infrasound and its effects on man. The Polish and international standards for measuring methods and occupational exposure limits have been discussed. A proposal of new limits of exposure to infrasonic noise in work environment has been presented. It was suggested that according to the health-based criteria an equivalent G-weighted sound pressure level normalized to a nominal 8-hour workday or 40-hour workweek should not exceed 102 dB. Additionally, the overall unweighted peak sound pressure level should not exceed, even instantaneously, 145 dB.

Introduction

International Standard ISO 7196 defines infrasound as the sound or noise with a frequency range from 1 Hz to 20 Hz. However, a current Polish Standard PN-86/N-01338 limits infrasound to the frequency range of 2-16 Hz. Moreover, it introduces the definition of „infrasonic noise". This term is referred to a broadband noise containing both infrasonic frequencies (2-16 Hz) and low audible frequencies (under 50 Hz).

Infrasound is ubiquitous in urban environment and the research conducted so far indicates that it may be a important source of many adverse effects on humans. The occurrence of infrasound is partly based on natural phenomena (e.g. winds, storms, waterfalls, earthquakes, volcanic eruptions), but most infrasound is produced by man-made sources, mainly related to industry. The examples are piston compressors, jet pumps, power boilers, fans, smelting furnaces, foundry devices, stationary Diesel engines, slow moving equipment etc. Infrasound is also commonly generated by the means of transport (e.g. cars, lorries, truck-tractors, locomotives, ships, helicopters, jet planes).

Effects of infrasound

It has been commonly assumed that infrasound is inaudible. However, this is now known not to be true. The perception of infrasound is based on hearing and vibrations. The sound-induced vibrations will be perceivable only at relatively high sound pressure levels, 20 to 40 dB above the hearing threshold. The sensory mechanism is the same as in detecting mechanically induced vibrations (Johnson[11], Landstrom et al.[12, 13], Landstrom and Pelmear[15]).

In general, the hearing sensations evoked by infrasound are often described as annoying. Single frequencies of infrasound are not perceived as pure tones. Instead they are often described as a rapid series of "pops" (5-15 Hz) or as "chugging" or "whooshing" sounds (below 5 Hz)(Evans[6], Johnson[11]). The ability to hear infrasound has therefore been suggested to be based on harmonics generated by distortion in the middle and inner ear (Johnson[11]).

The threshold of auditory perception rises rapidly as the frequency falls, from approximately 65 dB at 32 Hz to 95 dB at 16 Hz, 100 dB at 3 Hz, and 140 dB at 1 Hz (Landstrom and Pelmear[15]). The hearing threshold to broadband infrasonic noise is approximately 1-5 dB below the threshold curve for infrasonic pure tone (Landstrom[14]).

Since infrasound is not annoying when it cannot be heard or sensed, the hearing threshold should also serve as the threshold of human annoyance (Johnson[11]). But in everyday environment the sound pressure levels close to the hearing threshold are seldom described as unpleasant, since these levels are often masked by higher frequencies.

The annoyance associated with exposure to audible infrasound has been the subject of a number of laboratory experiments. For example, contours of equal annoyance were determined for pure tones within the frequency range from 4 to 31.5 Hz. The curves show a narrowing of the dynamic range of the ear at low frequencies. The same pattern is observed for equal loudness curves, so the annoyance of infrasound is closely related to the loudness sensation. Annoyance ratings of 1/3-octave noise do not deviate from ratings of pure tones with the same sound pressure level (Moller[16]).

One of the most conspicuous causes of the effects of annoyance caused by infrasound is the pressure sensation in the middle ear. This effect begins to occur for levels between 127-133 dB. It is often pronounced shortly after initiation of exposure and may sometimes persist also after exposure termination (Broner[4]).

The adverse effects of aural pain, speech interference and temporary threshold shift (TTS), normally appear at levels 30 to 40 dB above the hearing threshold. The threshold for aural pain is approximately 140 dB at 40 Hz and 160 Hz at 3 Hz. A tympanic membrane injury may be the result of exposure to extremely high sound pressure levels (Gierke and Nixon[7], Johnson[11]).

TTS effects from audiometric frequencies above 125 Hz have been observed after infrasound exposures at 140 dB. As expected, the most significant effects can be observed at frequencies above 1 kHz. The TTS, often of less than 10 dB, have been found to disappear rapidly after exposure (Broner[4], Johnson[11], Berglund and Hassemen[2]).

Infrasound as well as low frequency sound (10-75 Hz) may excite resonant vibrations in some parts of the human body e.g. abdomen, chest and throat. Such vibrations in the thorax/abdominal region normally appear at levels above 100-105 dB (40-60 Hz). The vibrotactile sensations in the abdomen and chest region due to infrasonic frequencies (4-20 Hz) appear at much higher levels, close to 130 dB (Evans[6], Johnson[11]).

An American space research project has indicated that the maximum permissible short-term exposure to infrasound should be in the region of 140-150 dB. Beyond this the chest walls of the subjects would vibrate, with a sensation of gagging and blurring of vision. Moreover, the chest wall vibrations may interfere with the respiratory activity (Johnson[11], Landstrom and Pelmear[15]).

Possible vestibular disturbances (described as the loss of the sense of balance, disorientation andnausea) have been investigated in several studies. The validity of these effects is controversial (Evans[6], Gierke and Nixon[7], Johnson[11]). In view of recent research, infrasound at the levels normally experienced by man should not have any significant effect on the vestibular function (Takigawa et al.[23]).

Physiological effects due to infrasound should only occur at levels when the sound can be heard or sensed. Since hearing perception occurs at levels below the vibrotactile sensation, the hearing threshold curve should also serve as a threshold for physiological effects (Borredon[3], Johnson[11]). Therefore, the sound pressure levels must always be high enough to allow perception, in order to induce physiological effects. This theory has been experimentally verified in laboratory studies. Reduction of wakefulness identified through changes in EEG, blood pressure, heart activity, respiration, and hormonal production, was found to occur only when the infrasound levels exceeded the hearing threshold. Under the same conditions the deaf subjects presented an absence of weariness (Landstrom et al.[12, 13], Landstrom[14]).

The physiological effects observed in experimental studies often seem to indicate a general slowdown of physiological and psychological functions. The reduction in wakefulness and related physiological responses are probably to be regarded as secondary reactions to a primary effect on the central nervous system (CNS). The effects of moderate infrasound exposure are thought to be based on the correlation between the hearing perception and the resulting CNS stimulation. The participation of the reticular activating system and the hypothalamus is considered to be of great importance (Landstrom and Palmear[15]).

However, the changes in the physiological reactions are not only ascribed to sound at levels above the hearing threshold. The response of the CNS (including RAS, hypothalamus, limbic system, and cortical region) are probably also highly influenced by the quality of sound. Thus, some frequencies and characteristics are probably more effective than others in producing weariness (Landstrom[14]).

Human exposure to infrasound in work environment very seldom occurs at high sound pressure levels; most exposures refer to moderate levels but infrasound is often accompanied by a number of other environmental factors (e.g. audible noise, vibration).

Normally occurring infrasound do not cause any dramatic health effects, but if they are above the hearing threshold they will produce symptoms including annoyance, weariness and unease. Besides the fundamental comfort reduction, the annoyance can result in disturbance and impaiment of the intellectual activity and in a reduction in working capacity.

Measuring methods

The draft proposal of international standard ISO 7196 suggested the use of two weighting characteristics (named G1 and G2) in order to describe infrasound in the frequency region below 20 Hz (Fig. 1). These curves were asymptotically weighted in straight lines with different slope. Between 1 and 20 Hz the lines had the slope of 12 dB per octave and 6 dB per octave for G1 and G2 curves, respectively. At frequencies above 20 Hz, both curves had cut-offs with the rates of 24 dB per octave. Below 1 Hz the slopes were 12 dB per octave and 18 dB per octave for G1 and G2 characteristics, respectively.

It is worth noting that the hearing threshold curves, equal loudness curves and equal annoyance curves have the slope close to 12 dB per octave. Thus, the background for the G1 curve was obvious. The G2 curve did not have a scientific basic; it was simply a result of a compromise between the G1 curve and linear curve. It is no wonder that G1 weighting filter gave values that corresponded much better with the subjective annoyance rating than G2 weighting filter (Moller[16]). Moreover, it is sometimes assumed that the sound pressure levels found on the $G1_{86\,dB}$ curve are the limit values of the hearing threshold, which is exceeded by 90-95% of the population (Fig. 2) (Vercammen[25]).

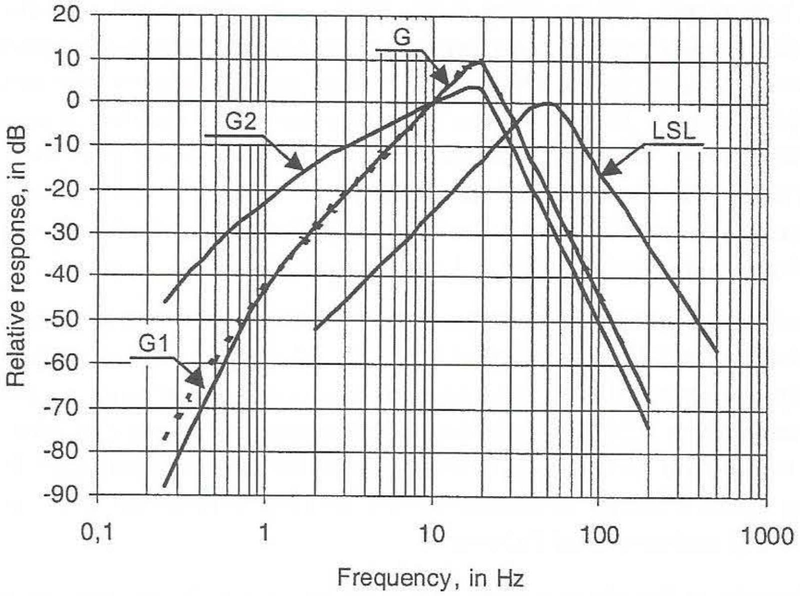

Figure 1: Nominal G1, G2, G and LSL weighting characteristics

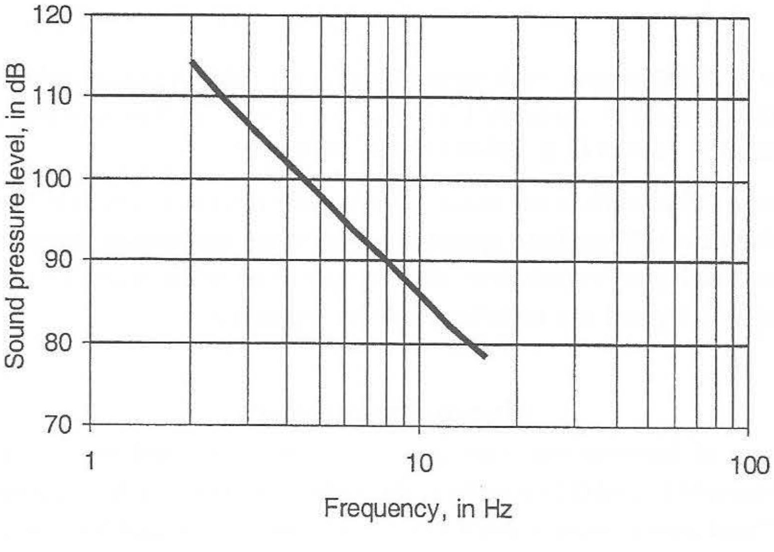

Figure 2: $G1_{86\,dB}$ curve (it is expressed as: $L=86-K_{G1}$, where: L – is the sound pressure level, in dB, K_{G1} – is relative response of G1-weighting filter, in dB)

In order to evaluate noise containing not only infrasonic but also the audible frequencies, especially in living environments, another type of frequency weighting curve named LSL (abbreviation for low frequency sound level) was proposed in Japan. It had a dominant frequency of 50 Hz and +12 dB per octave and -18 dB per octave slopes in the lower and upper range (Fig. 1) (Tokita and Shimizu[24]).

In the final version of ISO 7196 only the G1 curve was left and after slight modifications it was renamed as the G curve. The use of G weighting network is also recommend in the international standard ISO 9612 concerning the measurement and assessment of exposure to noise in work environment.

As the threshold of hearing perception defines human tolerance of infrasound it is sometimes thought that any pertinent hygienic evaluation of infrasound should consequently be based on the frequency analysis (Landstrom[14]). For example the frequency analysis using 1/3-octave band filters (in the frequency up to 20 Hz) is also allowed by the above mentioned standard ISO 9612. On the other hand, a current Polish standard PN-86/N-01338 recommends that infrasonic noisemeasurements should be performed using 1/1-octave band filters in the frequency range of 4-31.5 Hz.

Review of exposure limits for infrasound

The first proposals of criteria for infrasound exposure were presented at Colloquium on Infrasound, in Paris, in 1973 (Fig. 3). Later on, some countries included limits for maximum tolerable infrasound at workplaces in their noise legislation.

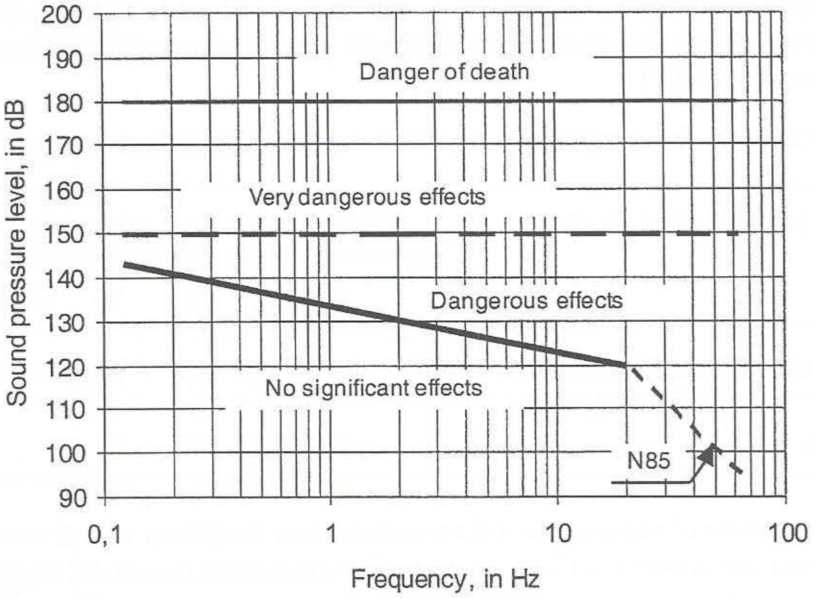

Figure 3: Limiting levels for effects of infrasound proposed by M. Stan (after Broner[4])

For example, in Sweden and Norway the permissible levels in the occupational environment were established in 1978. In Sweden, the limit for exposure to infrasound (2-20 Hz) for an 8-hour working day was 110 dB independent of frequency. For less than 1 hour of exposure it was 130 dB. In Norway, infrasound was defined to be in the 1/1-octave bands from 4 to 31.5 Hz with the permissible sound pressure level of 120 dB for 8 hours (Bruel[5]).

Due to the information about both the hearing threshold and the disturbances caused by infrasound, the Swedish exposure limits were modified in 1992. New permissible sound pressure levels (in 1/3-octave bands in the frequency range 2-20 Hz) are based on the hearing threshold of infrasound (Tab. 1). These values correspond with $G_{102\,\mathrm{dB}}$ curve and exceed the threshold of auditory perception by 5-10 dB. It was assumed that infrasound at sound pressure levels below these exposure limits is unlikely, in normal cases, to cause any effects (Ordinance AFS 1992:10[22]).

Table 1. Current Swedish limits for occupational exposure to infrasound (Ordinance AFS 1992:10[22])

Center frequency of 1/3-octave band, in Hz	2	2.5	3.15	4	5	6,3	8	10	12.5	16	20
Sound pressure level, in dB	130	126	122	118	114	110	106	102	98	94	90

In the former Soviet Union (Russia) the first limits for infrasound exposure were introduced in 1980. However, on the grounds of comprehensive physiological, hygienic, and experimental studies that revealed the pathogenic features of infrasound, a proposal has been made for new permissible levels. It suggests that the limits in 1/1-octave bands 2-16 Hz should decrease with a slope of 5-6 dB per octave (instead of 12 dB per octave according to ISO 7196) due to the priority of occurrence of the whole-body effects (Tab. 2). It is believed that everyday 8-hour exposure at these levels over the period of professional experience (up to 40 years) should prevent the development of any specific and unspecific diseases.

Russian researchers express the opinion that it is the vestibular system rather than the hearing organ that is responsible for the perception of infrasound. They also think that in humans the involvement of limbicoreticular complex, hypothalamus, and other subcortical structures in the responses to higher infrasound levels stipulates a prominent pathological discomfort as a manifestation of the infrasonic diencephalic hypothalamic syndrome with sensorisomatic and autonomic visceral symptoms (Izmerov et al.[10]).

Table 2. Russian limits for occupational exposure to infrasound (Izmerov et al.[10])

Sound pressure level, in dB	Center frequency of 1/1-octave band in Hz/filter					
	2	4	8	16	31.5	LIN
Ordinance of USSR Health Minister (1980)	105	105	105	105	102	110
Project (1996)	100	95	90	85	-	-

In 1998 the first limits of exposure to infrasound and low frequency sound were introduced to the guidelines of the American Conference of Governmental Industrial Hygienists. Except for impulsive sound with a duration of less than 2 seconds, the established Threshold Limit Value-Ceiling (TLV-C) is:

- 145 dB - for sound pressure levels in 1/3-octave bands for frequencies between 1 and 80 Hz, and
- 150 dB - for overall unweighted sound pressure level.

It is worth noting that TLV-C is an exposure limit which should not be exceeded even instantaneously. There are no time limits, except for the frequencies above 16 Hz due to the prevention of noise-induced hearing loss. However, the application of exposure limits for noise and airborne ultrasound may provide a reduced acceptable level with time. This reduction will depend upon the amount of attenuation allowed for the hearing protection.

An alternative, but slightly more constructive criterion assumes that peak sound pressure level measured with the linear or unweighted frequency response (extended to at least 2 Hz) of sound level meter should not exceed 145 dB.

It is believed that the established limits should prevent adverse effects that do not involve the hearing organ in almost all the population of exposed workers. But low frequency sounds in the chest resonance range (approx. 50-60 Hz) can induce a whole-body vibration. Such an effect may cause annoyance and discomfort. The sound pressure levels of such sound may need to be reduced to a level where the problem disappears (ACGiH[1]).

Current Polish admissible values. The above mentioned Polish standard PN-86/N-01338 first of all recommends the measuring method for infrasonic noise. However, it also specifies the admissible values of sound pressure levels for workers' health protection and to ensure proper conditions of work at two selected categories of workplaces (Tab. 3). These exposure limits were drawn up in 1986.

Since PN-86/N-01338 incorporates a 3-dB equal energy rule, the same as for the audible noise, each halving of duration (with relation to 8 hours) allows the 3-dB increase in the permissible sound pressure levels.

The ordinance issued by the Minister of Labour and Social Policy[19] restricts the range of assessment to 1/1-octave bands from 8 to 31.5 Hz and states the permissible levels for workers' health protection as a maximum admissible intensity (MAI) values for infrasonic noise in work environment.

Table 3. Admissible values of the sound pressure levels at workplaces as specified in PN-86/N-01338 (exposure time – 8 hours)

Permissible sound pressure levels, in dB	Center frequency of 1/1 octave band, in Hz			
	4	**8**	**16**	**31.5**
For health protection at all workplaces (MAI)	110	**110**/*137**	**110**/*137*	**105**/*132*
To ensure proper conditions for performing basic functions in observational dispatcher cabins, remote control operations, on premises for precise works etc.	90	90	90	85
On premises for administration, design offices, research work, data handling etc.	85	85	85	80

* Bold figures – a limitation introduced in the Ordinance by the Minister of Labour and Social Policy; in italics – maximum permissible levels for short-term exposure

Separate regulations have been issued for groups of workers at particular risk (Ordinance by the Cabinet [17, 18]). Accordingly, pregnant women and juveniles must not be employed at the workplaces for which the sound pressure levels exceed the admissible values displayed in Table 4.

Table 4. Infrasonic noise: admissible values for groups of workers at particular risk as specified in current Polish regulations

Center frequency of 1/1 octave band, in Hz	4	8	16	31,5
Sound pressure level, in dB	85*	85	85	80

* The 1/1-octave band of 4 Hz is consideration only for the juvenile workers

Proposal of new Polish exposure limits for infrasonic noise

The threshold of auditory perception defines human tolerance of infrasound. Although the current Polish admissible values for workers' health protection are in fact the admissible values for hearing protection, they are not connected with the hearing threshold of infrasound that the G weighting curve is related to.

A few years ago the infrasonic noise measurements were performed at various workplaces in order to evaluate the actual exposure in the occupational setting in Poland. The study concerned 124 different types of industrial machinery and means of transport, e.g. turbogenerators, power boilers, fans, coal pulverizers, compressors, pumps, devices used in petrochemistry and chemical plants, smelting furnaces, foundries, electric and diesel locomotives, small crafts, ferries, buses, trams, lorries, truck-tractors, road making vehicles, flour mill machinery etc. Sound pressures levels exceeding the admissible values were found only in 4.0% cases, while as much as 66.9% of the industrial machinery and means of transport appeared to generate infrasonic noise at the levels exceeding the $G_{86\ dB}$ curve (hearing threshold of infrasound) (Pawlaczyk-Łuszczyńska[20]).

Proposals of new limits for occupational exposure to infrasonic noise were put forward based on a comprehensive analysis of:

- literature data concerning the effects of infrasound on humans,
- the existing standards and occupational exposure limits, especially Swedish and American,
- results of our own infrasonic noise measurements performed in the work environment.

It was assumed that the assessment of occupational exposure to infrasonic noise would be based on the following:

- equivalent G-weighted sound pressure level normalized to a nominal 8-hour workday or 40-hour workweek ($L_{G\ eq,\ 8h}$ or $L_{G\ eq,\ w}$), expressed by equations (1), (2), (3):

$$L_{G\,eq,T} = 10\ \log\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\left(\frac{p_G(t)}{p_o}\right)^2 dt\right] \qquad (1)$$

$$L_{G\,eq,8h} = L_{G\,eq,T_e} + 10\log\frac{T_e}{T_o} \qquad (2)$$

$$L_{G\,eq,w} = \frac{1}{5}\sum_{i=1}^{N} 10^{0,1\cdot(L_{G\,eq,8h})_i} \qquad (3)$$

where

$L_{G\ eq,\ T}$ – is the equivalent G-weighted sound pressure level, in dB,
$p_G(t)$ – is the instantaneous G-weighted sound pressure, in Pa,
p_o – is the reference sound pressure (= 20 mPa),
$t_2 - t_1$ – is the period T over which the average is taken starting at t_1 and ending at t_2,
T_e – is the effective duration of exposure within a workday,
T_o – is the reference duration (= 8 h),
$(L_{G\ eq,\ 8h})_i$ – is the equivalent G-weighted sound pressure level normalized to a nominal 8-hour workshift on day i,
N – is the total number of workdays during a week,

- overall unweighted peak sound pressure level ($L_{LIN\ peak}$), with linear response of the measurement instrument extended down to at least 2 Hz, that should not be exceeded, even instantaneously.

It is worth noting that $L_{G\,eq,\,w}$ will be determined only if the exposure to infrasonic noise varies over a working week. Thus, the proposed admissible values for workers' health protection are:

- 102 dB – for an equivalent G-weighted sound pressure level normalized to a nominal 8-hour workday or 40-hour working week,
- 145 dB – for unweighted peak sound pressure level.

The sound pressure level of 102 dB(G) is associated with the $G_{102\ dB}$ curve that the Swedish exposure limits correspond to. The admissible value of unweighted peak sound pressure level as stated in the ACGiH guidelines was the reference value in our proposal. It is believed that the proposed limits should prevent any adverse effects, not only those relating to the hearing organ, in almost all the population of exposed workers (Fig. 4).

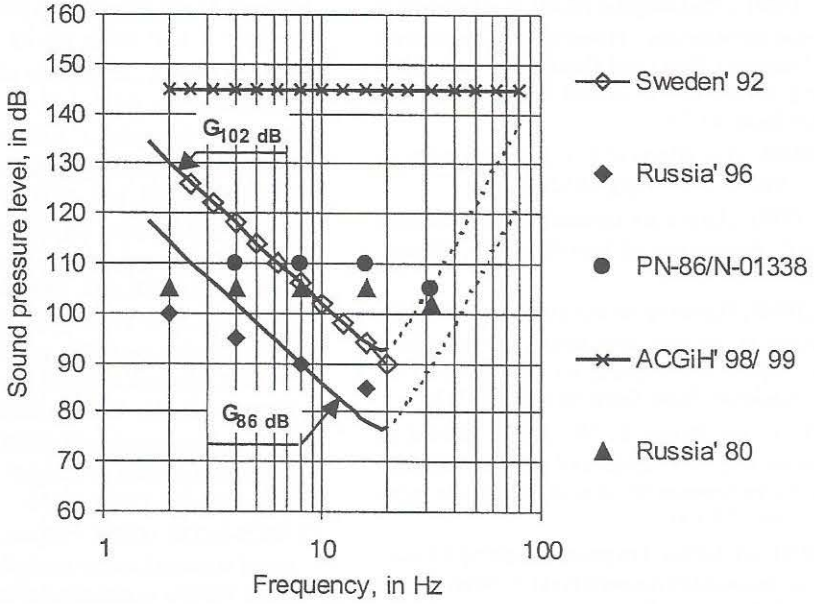

Figure 4: G_{102dB} and G_{86dB} curves compared to existing or proposed limits for occupational exposure to infrasound

The proposed exposure limits for workers at particular risk i.e. pregnant women and juveniles, are as follows:

- 86 dB – for an equivalent G-weighted sound pressure levels normalized over a nominal 8-hour workday,
- 145 dB - for unweighted peak sound pressure level.

The sound pressure level of 86 dB(G) corresponds to the $G_{86\ dB}$ curve that it is assumed to be the threshold of auditory perception of infrasound.

Conclusions

The proposed limit values for occupational exposure to infrasonic noise:

- are based on up-to-date data concerning the health effects of infrasound on humans,
- take into consideration respective international standards i.e. ISO 7196, ISO 9612,
- have been accepted by the Intersectoral Committee for Setting Occupational Exposure Limits and will be considered as when developing the new Polish regulations regarding occupational exposure to physical hazards.

Acknowledgements

The study was conducted as a part of the research project within the Strategic Government Programme (SPR 02.3.5) supported by the State Committee for Scientific Research of the Republic of Poland.

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Digit skin temperature test for peripheral circulation evaluation.

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3) Vasogen Inc., Toronto, Canada.

Summary

A test procedure for evaluating vasospasm in hand digits using cold water immersion at 15°C for a period of 10 minutes is described and the results of initial and repeat tests on 25 subjects who volunteered for a control group study are reported. Five from their history and test results were determined to have Raynaud's disease or Constitutional White Finger, and a further 5 subjects with no history of cold hands or Raynaud's phenomenon had non-repeatable test results indicative of an asymptomatic sub-clinical state. Control subject reference data (means and standard deviations) is provided.

Introduction. To identify and quantify the severity of Raynaud's phenomenon (RP) numerous laboratory tests have been introduced by researchers over the years. These have included plethysmography (photocell or strain gauge) to demonstrate digit pulse wave changes pre- and post-cold water immersion at temperatures of 0 to 15°C for up to 2 minutes [Pelmear et al.[1], Pelmear and Taylor [2]]; digit temperature measurement - cold water immersion at 0 to 15°C for up to 10 minutes, with recording of skin temperature to note a hyperaemic response, if any, while immersed, and following immersion to note the recovery rate of each digit over time [Pelmear et al.[1], Pelmear and Taylor[2], Bartelink et al.[3], Juul and Nielsen[4], Gautherie et al.[5]]; finger systolic pressure measurements at 10, 15 and 30°C temperatures of the middle or worst affected digit using the thumb or brachial artery as a reference control [Pelmear et al.[1], Pelmear and Taylor[2], Nielsen and Lassen[6], Bovenzi[7], Corbin et al.[8], Ekenvall and Lindblad[9], Bovenzi et al.[10]]; and laser doppler blood flow measurement [Bartelink et al.[3]].. Each test has it's advocates, but, the use of a particular test has depended on the availability of the test to the investigating physician, and the preference of the laboratory or researcher.

The Department of Occupational & Environmental Health, St. Michael's Hospital, Toronto for their evaluation of hand-arm vibration syndrome (HAVS) patients chose to determine in their laboratory the severity of vasospasm using the digit temperature measurement test, together with Doppler and plethysmography tests which were available through the vascular laboratory at Sunnybrooke Hospital. With Doppler ultrasonic instrumentation the blood flow and systolic pressures in the brachial, radial and ulnar arteries may be recorded and any abnormalities in these blood vessels identified. Using photocell or strain gauge plethysmography the finger and toe pulse waveforms can be compared before and after cold stress following immersion in water or exposure to air at 10°C for 2 minutes.

Variations in wave form patterns may be detected, and the absence of a dicrotic notch with a slow up stroke always indicates organic disease. Patients who suffer from vasospasm usually have a normal waveform at room temperature, but after exposure to cold the waveforms become abnormal and may be completely flattened if vasospasm is severe [Pelmear and Taylor[2]]. It must be appreciated that the determination of abnormality and severity is made on the appearance of the waveform at two points in time - immediately following cold stress, and 3 minutes later. It does not permit an evaluation of recovery over a more prolonged period of time which is desirable for a more factual indication of severity. Some patients will have severe vasospasm with a quick recovery, while others will have a slower recovery over a prolonged period of time and this is indicative of increased impairment. The interpretation of the result of this test is subjective so this also is a disadvantage.

By monitoring digital skin temperatures an indirect assessment of vasodilation and vasospasm in digital arteries can be obtained [Bartelink et al.[3], Juul and Nielsen[4], Gautherie et al.[5]]. With the arteries normally dilated at room temperature, baseline digit skin temperatures are recorded. The digits are then immersed in cold water or air and as the arteries constrict with vasospasm in response to cold-stress there will be a corresponding decrease in skin temperature. Normal digital arteries will respond with post-ischemic reactive hyperaemia while still immersed, and rapid recovery following immersion. When significant vasospasm occurs there is no reactive hyperaemia and recovery is prolonged - the rate of recovery depending on the severity.

A cluster analysis technique (SAS FASTCLUS procedure[11]) is useful for the objective analysis of the results of many diagnostic tests on a large group of individuals so Pelmear et al.[12], and Pelmear and Kusiak[13] used this procedure to review 364 HAVS patients who were assessed during the period 1989-92. Because of exclusions due to confounding factors, 173 men were available for analysis. Four vascular and four sensorineural categories of impairment were recognised, and there was an association with the Stockholm Workshop scales [Gemne et al.[14], and Brammer et al.[15]]. The vascular stages equated to the four vascular clusters, and although it is more difficult to equate four sensory clusters with three sensorineural Stockholm stages it appeared that the Stockholm stages 1 to 3 equated to clusters formed from the sensory tests evaluating the sensitivity of the mechanoreceptors and the distal digital branches of the median and ulna nerves. When the myelinated fibres are affected as determined by the Tinel's, Phalen's, and nerve conduction tests, an additional cluster group emerges. Thus the patients with abnormal nerve conduction tests constitute a distinct group so a Stockholm Stage 4SN is required if and when there is a revision of the scales. Meanwhile, the present Stockholm 3SN needs to be restricted to cases with abnormal nerve conduction tests.

A comparison of the vascular and sensory clusters showed that while some men suffered severe vascular effects and others suffered severe sensory effects few suffered from both. Hence, the severity grading of the vascular and sensory components must be evaluated separately. The analysis of the digit skin temperature data in respect of recovery temperatures at 3 and 7 minutes post-cold stress, enabled temperature ranges and mean temperatures to be derived for the Stockholm stages and these are presented in Tables 1 and 2. The use of this reference data permits both an objective and subjective interpretation of the test result.

It will be noted that this data is obtained only from vibration exposed patients. Although previous field studies [Pelmear et al.[16,17]] have provided reference data for digit temperature recovery rates following cold provocation in control subjects, there are few if any reports in the literature of reference data for control subjects investigated in a laboratory environment. To correct this deficiency the following study was conducted.

Selection of subjects for Control Group study. Twenty-five hospital staff volunteered to be interviewed and tested for a control group study, the protocol having been accepted by the Wellesley Central Hospital Ethics Committee. All were carefully screened by questionnaire and examination to exclude those with hand injuries and significant illnesses. All were non-smokers. The additional rejection criteria adopted was for two or more of the following to be present:

- history of Raynaud's phenomenon or complaints of cold hands.
- initial skin temperature of digits less than 30°C.
- final skin temperature less than 30°C.
- no significant post-ischemic hyperaemia during cold water immersion.

Five subjects were rejected on this basis.

Test Methodology. It was not feasible to conduct the clinical test in a purpose built climate controlled room, so the room temperature recorded with all subjects ranged from 21 to 24°C (mean 22.5°C) and the humidity from 45 to 65% (mean 55%).

The test procedure for the hot water/cold water bath immersion test was as follows;

- both water baths were turned on 30 minutes prior to the testing of a subject to allow the water in the tanks to heat and cool to 40°C and 15°C respectively.

- the subject was positioned in a chair and wrapped in an electric blanket to control and maintain central body temperature at approximately 37°C.

- numbered thermocouples were taped (using 3M Transpore Surgical No 1527/1) to the tips of the digits of the right hand (i.e. #1 thumb, #2 index, etc., with #6 in the water bath), and the wires were supported by velcro strapping around each digit. The thermocouples were attached to a Progeny TM RSX video continuous temperature recorder (Honeywell Ltd.) from which all data points and patient information could be down-loaded to a disc for transfer to a computer programmed with simple translation software.

- a blood pressure cuff was placed around the lower right forearm.

- the subject's identification data - file name and number was entered on the RSX recorder and the recording started.

- ambient room temperature and humidity were recorded before and after the testing of each subject.

- the room temperature and digit baseline temperatures were recorded for 5 minutes, then the right hand was immersed in the hot water bath at 40°C to the level of the MP joints of the fingers for 5 minutes. The bath temperature and the digit temperatures were recorded continuously.

- the right hand was then immediately transferred into the cold water bath at 15°C and the blood pressure cuff was inflated to 30 mms above the systolic pressure. The cold bath temperature and the digit temperatures were recorded continuously.

- the cuff was released after 5 minutes with the hand remaining in the cold water bath for a further 5 minutes.

- at 10 minutes following immersion the hand was released from the cold water bath, the velcro straps were removed, and the skin was lightly dried with a towel.

- the recording disc continued to accept recovery temperatures from the digits for a further 10 minutes, while the room temperature was also recorded continuously.

- the entire procedure was repeated with the left hand.

Subject analysis. Three months after the initial test on both hands of all the volunteers, the test was repeated on all of them. Following the repeat test a further five subjects were identified with two test results differing very significantly, indicating possible unstable vasomotor control i.e. pre-symptomatic Raynaud's disease. Thus, four groups were identified for data analysis - fifteen acceptable controls with repeatable test results (11♀,4♂, mean age 38); five suspect controls with significant differences between the test results (4♀,1♂, mean age 43); fifteen acceptable and five suspect controls (5♀,15♂, mean age 40); and five suspect controls combined with five rejected subjects (7♀,3♂, mean age 43). Table 3 gives the demographic factors of the acceptable controls, suspect controls and the reject subjects.

The data from the recording discs was transferred by direct entry for computer analysis. Using a SAS program[11], the temperature measurements of each of the five digits and the average for the hand were calculated as follows:

- average temperature over the whole initial baseline period (5 minutes) for the five digits and the average for each hand.
- the average temperature over the last thirty seconds in the hot bath.
- the area under the curve (temperature by time) in the hot bath.
- the average temperature over the whole period (10 minutes) in the cold bath.
- the maximum temperature achieved in the cold bath after the release of the pressure cuff.
- the last temperature reading prior to removal of the hand from the cold water bath.
- the last recorded temperature at ten minutes recovery in air.
- the area under the curve (temperature by time) in the recovery period in air.
- the area under the curve (temperature by time) for each one minute period during the recovery period in air.

A statistical analysis of the calculated measurements for the specific end-points was undertaken. The overall digit skin temperature measurements were compared between the left and the right hands, and between the first and second tests using a multivariate linear regression analysis.

Results. There was a marked uniformity in the digit skin temperature responses of the 15 acceptable controls throughout the test time period, with good post-ischemic hyperaemia while immersed, and a rapid recovery following immersion in both the initial and repeat tests. Comparing the left and right hands, the only statistically significant difference between all the digit temperature measurements was in the mean temperature prior to cold water immersion (Table 4). The left hand was slightly warmer (0.3°C). This was probably due to the fact that the body blanket was in operation for 10 minutes prior to the right hand being tested, and for 40 minutes prior to the left hand being tested.

The means of the finger tip skin temperatures and their standard deviations, for both hands combined, from the results of the initial and repeat tests in the 15 acceptable controls are given in Table 5. In a similar comparison of the left and right hand measurements in the 5 suspect and 5 rejected subjects there was significant scatter with slower recovery and lower final temperatures, and almost every end-point presented a statistically significant difference between the hands and/or the repeat test.

Discussion. The presence and severity of Raynaud's phenomenon in patients may be confirmed by noting the digit skin temperatures reached during immersion in cold water, the extent of the post-ischemic reactive hyperaemia if any, and the recovery time following immersion. In the normal subject, after the sphygmomanometer cuff is released, there is a reactive hyperaemia while immersed, and rapid recovery to baseline digit skin temperature within 10 minutes of exposure of the hand to room air temperature. The pressure cuff causes some ischaemic pain until it is released. Although the hyperaemic reaction may be more evident when it is used the more important recovery time feature is not affected, so it's use is no longer considered to be necessary. As vasospasm from cold-stress increases in severity a post-ischemic hyperaemic reaction is less evident or absent, and recovery in air is increasingly prolonged.

Recovery of skin temperature following cold stress in patients with Raynaud's phenomenon depends on the release of vasospasm (local and centrally induced), but delay in recovery may also occur in patients with impaired blood flow because of peripheral vascular disease. The latter may be diagnosed from the medical history and the results of additional vascular tests e.g. Doppler, arteriography etc.

It has been well established that the prevalence of Raynaud's phenomenon due to Raynaud's disease or Constitutional White Finger may be between 5 and 30% in the general population [Coffman[18]], with a 5 to 1 female/male ratio. These statistics are derived from the reported observation of finger blanching by subjects following exposure to cold or stress. Although the majority of these patients will have first observed the phenomenon as a teenager, only 60% of those who suffer from Raynaud's disease (constitutional white finger) do so by age 30, and 81% by age 40 [Coffman[18]]. Therefore, as the onset is gradual, sub-clinical (pre-symptomatic) cases will exist in the population at any point in time. A history of finger blanching, or cold hands and/or feet in a relative is a useful indicator as to the possibility of vasospasm being due to Raynaud's disease, also a tendency for cool hands and feet in the subject, but many apparently normal subjects going on to develop Raynaud's phenomenon are in a pre-symptomatic state. This sub-clinical state in individuals can be identified by laboratory tests, and when the initial test result is not obviously positive, a variability in subsequent test results will indicate a vasomotor instability which is indicative of the sub-clinical state. Hence, to obtain valid normative reference data a control population should be carefully screened, by history and repeat laboratory testing.

Using the basic rejection criteria mentioned earlier to identify subjects to be rejected, and then conducting an initial and repeat cold water immersion test on all subjects permitted the identification of very different response groups. The acceptable control group subjects (those with two repeatable test results) were remarkably homogenous in their response to cold stress, while the suspect controls and rejected subjects were not. The reliable normative reference levels as obtained in this study are given in Table 5.

Conclusion. The cold water immersion digit temperature test is a reliable, inexpensive, and objective test for determining the presence of and for evaluating the severity of Raynaud's phenomenon associated with any condition. The results are repeatable except in patients with sub-clinical Raynaud's disease. Normative reference data derived from the evaluation of properly screened controls will enable abnormal subjects to be identified, and the different rates of recovery in HAVS patients permits the severity of vasospasm to be staged according to the Stockholm vascular scale.

Acknowledgements. The authors wish to acknowledge the support of Vasogen Inc., and Ms Rosenberg and Ms Breslin for their assistance in the collection of data.

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Digit temperature test reference levels for HAVS by Stockholm vascular stage.

Tables 1 and 2 list the mean temperatures in degrees centigrade reached above the cold water bath temperature at 3 and 7 minutes post-cold water immersion with 95% confidence intervals for the four cluster analysis vascular groups. The range of temperatures for each cluster group, derived by discriminate analysis, is also included.

Table 1: *At 3 minutes post-cold stress*

Stockholm Stage	Severity	Temperature range °C	Mean temperature	95% Confidence limits
4	Very severe	< 4.9	3.7	1.1 to 6.3
3	Severe	4.9 to 8.7	6.0	2.9 to 9.1
2	Moderate	8.8 to 12.3	11.6	6.0 to 17.2
1	Mild	12.4 or more	13.1	8.1 to 18.1

Table 2: *At 7 minutes post-cold stress*

Stockholm Stage	Severity	Temperature range °C	Mean temperature	95% Confidence limits
4	Very severe	< 9.9	6.8	1.7 to 11.9
3	Severe	9.9 to 13.6	13.2	6.5 to 19.9
2	Moderate	13.9 to 16.3	14.5	11.0 to 17.9
1	Mild	16.4 or more	18.1	14.5 to 21.8

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Table 3. *Demographic Factors*

	CONTROLS	SUSPECTS	REJECTS
Sample Size	15	5	5

Sex Male/Female	4 / 11	1 / 4	2 / 3
Age Mean ± Std (Range)	37.73 ± 7.60 (27-57)	42.80 ± 12.97 (29 - 63)	43.00 ± 7.48 (33 - 51)

Table 4. ***Mean and Standard Deviations in Hand Digit Temperature Measurements for Left and Right Hands at Visits 1 and 2, in 15 acceptable Controls***

Mean (Std Dev)		**Right Hand**		**Left Hand**		**p Value**	
		Visit #1	**Visit #2**	**Visit #1**	**Visit #2**	**Left vs Right**	**Visit 1 vs 2**
Baseline	**mean temperature**	35.59 (1.21)	35.62 (.59)	35.91 (.74)	36.00 (.57)	0.07	
Hot Water	**mean temperature last 30s**	39.51 (.29)	39.35 (.32)	39.52 (.42)	39.38 (.31)		0.05
	area under curve	11364 (231)	11343 (262)	11279 (320)	11439 (277)		
Cold Water	**mean temperature**	18.58 (.75)	18.53 (.61)	18.85 (.79)	18.89 (.71)	0.02	
	last temperature	19.01 (1.81)	18.48 (1.31)	19.32 (2.55)	19.32 (2.12)		
	max temperature in last 5 min.	19.91 (2.01)	19.69 (1.49)	20.54 (2.18)	20.31 (1.80)	0.07	
Recovery	**last temperature**	35.33 (.81)	35.36 (.51)	33.71 (4.97)	35.52 (.56)		
	area under curve	18787 (1638)	18817 (1213)	18370 (3853)	19547 (1588)		
	area under curve minute 1	1420 (259)	1343 (155)	1401 (276)	1423 (262)		
	area under curve min 2	1621 (328)	1571 (224)	1605 (305)	1642 (321)		
	area under curve min 3	1752 (327)	1744 (199)	1764 (275)	1805 (295)		
	area under curve min 4	1862 (277)	1891 (111)	1868 (263)	1923 (216)		

Table 5. *Mean and Standard Deviations in Hand Digit Temperature Measurements with both hands combined in 15 acceptable Controls*

	Mean Temperature	Standard Deviation
Baseline	35.785	0.92
Hot Water Bath	39.268	0.506
Last 30 Secs in Hot Water	39.439	0.339
Cold Water Bath	18.713	3.022
Last Recording in Cold	19.03	1.98
Max. in Last 5 Min. Cold	21.382	1.83
Last Recording Recovery	34.979	2.591
1st Min. Recovery	23.18	4.393
2nd Min. Recovery	26.822	4.938
3rd Min. Recovery	29.426	4.585
4th Min. Recovery	31.433	3.768
5th Min. Recovery	33.046	2.716
6th Min. Recovery	34.16	1.562
7th Min. Recovery	34.744	1.058
8th Min. Recovery	35.054	0.847
9th Min. Recovery	35.235	0.772
10th Min. Recovery	35.369	0.77

Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

LOW-FREQUENCY NOISE EMISSION OF FINNISH LARGE-CALIBRE WEAPONS

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Summary

Noise emissions from large-calibre weapons were measured in a shooting area according to Danish guidelines. At a distance of 100 m the peak levels (L_{Cpeak}) were 146-159 dB for the bazooka, 148-163 dB for the 155-mm cannon, 147-151 for the mortar, 128-141 dB for the antiaircraft cannon and 146-155 for the 1-kg TNT explosion. The C-weighted exposure levels (L_{CE1s}) were 127-136 dB for the bazooka, 134-140 dB for the 155-mm cannon, 122-129 dB for the mortar and 104-115 dB for the antiaircraft cannon. Sound directivity proved to be a significant parameter for weapons. The most prominent octave bands were typically lower than 100 Hz.

Introduction

The Finnish Defence Forces (FDF) practise on shooting ranges and in reserved shooting areas. Rifle calibre weapons are used on shooting ranges, whereas large-calibre weapons are shot either in areas especially reserved for shooting or at test shooting stations. In addition, there are other areas where combat exercises are arranged. The limit between the rifle-calibre and large-calibre weapons is 12.7 mm, and 12.7 mm is considered as large calibre. The FDF have prepared for handling possible complaints and discussions by consulting Scandinavian, national and local environmental authorities, getting information, and buying measurement equipment and noise calculation programs. Currently, calculation programs are being used only for rifle-calibre shooting ranges, but there is trend towards the use of models, for the spreading of noise also for large-calibre weapons.

For the noise exposure of large-calibre weapons no special limit or guide values have been set in Finland. In addition, the correction needed for the impluses produced by this type of noise has not been determined. Therefore, the noise and noise emission of large-calibre weapons needs to be studied. So far, the complaints concerning the noise of large-calibre weapons have been few and random, since the shelter area around the shooting areas has generally been sufficient. The residents living nearby have also mostly had a positive attitude towards this type of noise. When complaints emerge, the environmental section of the FDF has measured the noise immission and analysed the situation together with the local environmental officials. Since local environmental officials generally have no measurement equipment for the analysis of low-frequency impulse noise at their disposal, difficult and complicated situations have been analysed as research projects. Sometimes also the ground vibration caused by the shots has been studied.

Data in noise emission and environmental noise values have been gathered for large-calibre weapons as an aid to for evaluation situations in general. One goal has been to gather information for modelling or the use of foreign models in noise evaluations [1-4]. In addition, hearing protection, product development, noise evaluation made during initial inspection of the weapon, and constructional and environmental analyses have been other goals.

The noise of large-calibre weapons consists typically of muzzle blasts, flight noise of grenades, and the noise of hit explosions. According to the Finnish Ministry of the Environment the legistlation on rifle-calibre shooting noise (VNp 53/97) is not applicable to large-calibre weapon noise. As a result, there has been much discussion on the noise limits between the Finnish Ministry of Social Affairs and Health, the Ministry of the Environment, the Ministry of Defense and specialists. The basic agreement has been that the daily equivalent level ($L_{Aeq7\text{-}22}$) of 55 dB should be applied as the general environmental limit value, but impulse correction is still an open question. Therefore, an attempt is being made to gather information on the impulse noise of large-calibre weapons, and it has been going on for a few years. The equation combining some of the parameters is shown as (1)

$$L_{Aeq7\text{-}22} = L_{AEto} + 10\log n + 10\log(t1/to) + 20\log(r1/ro) + K1 + K2, \tag{1}$$

where
L_{AEto} = noise emission value at distance ro (to = 1 s and ro = 100 m)
n = daily number of shots
$t1$ = daily calculation duration (7-22 equals $t1$ = 15 h = 54000 s)
$r1$ = calculated distance, m
$K1$ = correction for impulse properties, 1-10...20 dB
$K2$ = corrections for ground, obstacles, weather, etc

According to a study for the Swedish Defence Forces [5] 95 dB as L_{CE1s} is an appropriate guideline for the environmental noise of large-calibre weapons for areas where the number of shots exceeding 90 dB (L_{CE1s}) is over 100 annually, whereas 100 dB should be used for areas where there are fewer than 100 annual shots. According to the report shooting during evenings and nights should be restricted when the limits are exceeded. For new shooting areas, it is recommended that the values be 5 dB lower.

Noise control work [6-10] has also been done when needed. Noise barriers are needed for both safety and noise attenuation purposes. Houses for shooting control and bunkers for shooters have been especially contructed to have sufficient noise attenuation properties. However, the noise attenuation properties of the terrain and surface, obstacles, vegetation, and weather conditions and especially the effect of the impulse properties of noise need more research.

This text explains our effort to measure the noise emission of large-calibre weapons for the purposes described. These results will be used for noise evaluations and for future guidelines for environmental noise.

Materials and methods

Noise emissions from large-calibre weapons were measured in a shooting area according to Danish guidelines [1].

The following weapons were used: a 23-mm antiaircraft cannon (23AAC), a 95-mm bazooka (95B), a 120-mm mortar (120M) and a 155-mm cannon (155C). In addition, explosions of 1 kg TNT were used as reference measurements so that parameters could be calculated for the weather, sound directivity and ground effect.

The measurement site was not quite sufficient according to Danish criteria (300x300 m open flat terrain) because, for safety reasons, the shooting was carried out at typical test shooting sites. However, there was about 100 m of open flat terrain around the weapons.

The emission values were measured at a distance of 100 m from the muzzle of the weapon at angles of 0, 45, 90, 135 and 180 degrees from the shooting direction. Noise measurements were made at a height of 1.5 m from the ground by sound level analysers B&K 2260. C-weighted peak and impulse levels (L_{Cpeak} and L_{CImax}), exposure levels (L_{CE1s}), A-weighted impulse levels (L_{AImax}) and exposure levels (L_{AE1s}) were recorded. In addition, the equivalent octave levels from 16 to 8000 Hz were calculated over 1 second (L_{oct1s}). The presented values represent average values of five consecutive shots.

The weather conditions were +5 - +15 °C, wind at < 5 m/s, and typically cloudy.

Results and discussion

At a distance of 100 m the peak levels (L_{Cpeak}) were 146-159 dB for the bazooka, 148-163 dB for the 155-mm cannon, 147-151 for the mortar, 128-141 dB for the antiaircraft cannon and 146-155 for the 1-kg TNT explosion. The C-weighted exposure levels (L_{CE1s}) were 127-136 dB for the bazooka, 134-140 dB for the 155-mm cannon, 122-129 dB for the mortar and 104-115 dB for the antiaircraft cannon. Sound directivity proved to be a significant parameter for the weapons. The most prominent octave bands were typically lower than 100 Hz. Appendix 1 shows more accurate values for the octave band analyses. Figure 1 shows an example of the directivity of the shot of a 155-mm cannon as C-weighted 1-second exposure values. This directivity diagram is a result of a muzzle brake that causes the pressure pulse to be directed backwards and sidewards.

A collected directivity figure for several weapons can be seen in Figure 2, in which the A-weighted 1-second exposure levels have been shown. An example of the frequency content can be seen in Figure 3, in which a shot of a 155-mm cannon has been analysed at 135 degrees from the shooting direction. The noise was of low frequency. The noise impulse of large-calibre weapons contains a significant amount of low-frequency noise energy, and this energy explains the differences that can be seen when Figures 1 and 2 are compared.

The measured values can be used as the input values for calculation programs, but they can also be used as estimates for various distances even in simple hand calculations. The results are roughly comparable to respective NATO weapon emission values. In Finland a few complaints have been made annually about the noise coming from shooting areas for large-calibre weapons. However, so far, most of the residents in the surroundings have accepted the noise of military exercises involving large-calibre weapons.

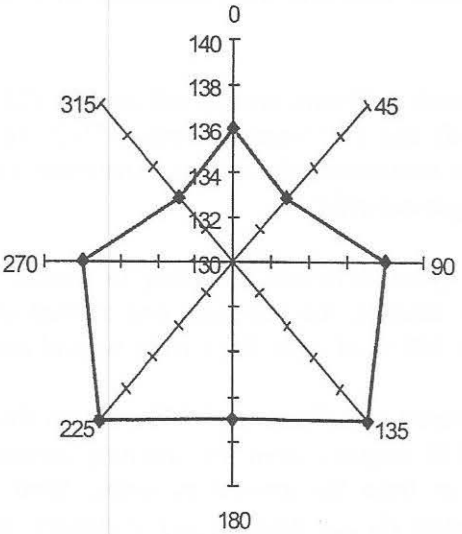

Figure 1. Noise directivity of a 155-mm cannon shot

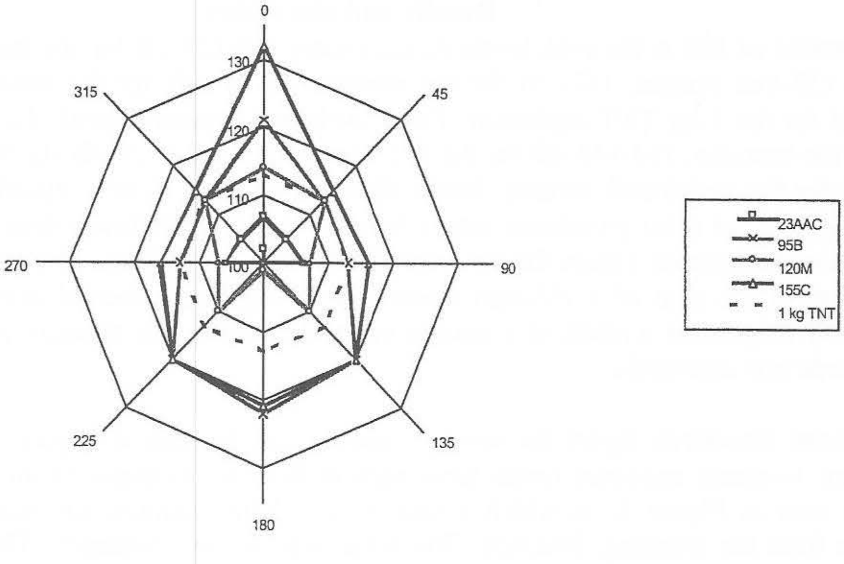

Figure 2. Directivity of some large-calibre weapons measured as the A-weighted 1-second sound exposure level at a distance of 100 m.

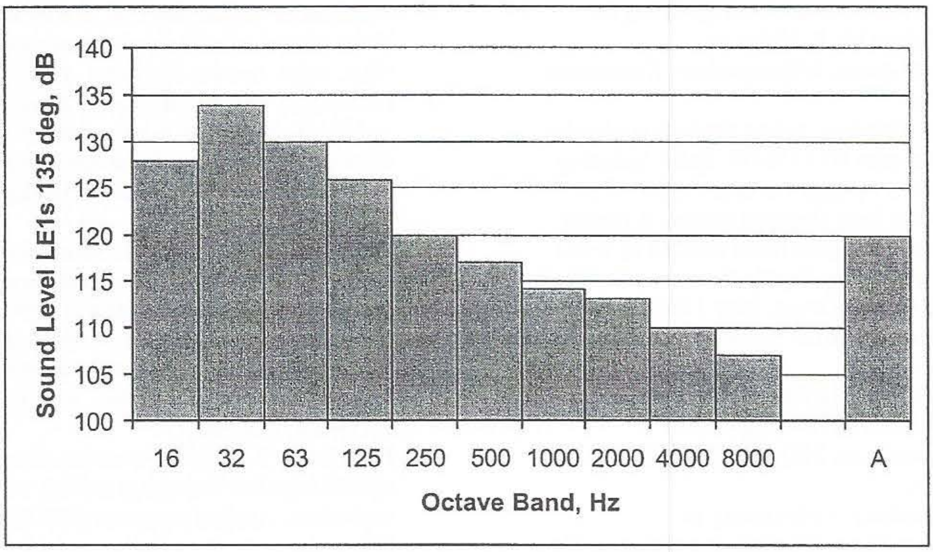

Figure 3. Directivity and frequency response of the sound from a 155-mm cannon

The explosion of 1 kg TNT proved to be an adequate reference for larger-calibre weapons, for example, for calibres over 30 mm, but for calibres 12.7 through 30 mm also 100 g TNT would probably be more relevant when comparisons are being made with the noise properties and spectrum of the measured weapon.

As earlier stated, the noise from large-calibre weapons consists of muzzle blasts, flight noise and hit impacts. In our measurement results only partial flight noise is present in the direction of 0 degrees from the shooting direction. When environmental noise is evaluated, the flight noise should be also considered, especially to the side and diagonally toward residential areas. Flight noise analyses depend also on the elevation angles of weapons, and therefore the modelling has separate parameters. We measured flight noise in some cases to be able to estimate this type of environmental noise, and it can be important when the elevation angle is small. However, the spectrum is higher in frequecy, and therefore this noise is attenuated better than muzzle blast noise.

In Finland we have not yet determined which parameters are needed for evaluating large-calibre weapon noise. The situation seems to be the same elsewhere. Therefore we measured numerous parameters to able to compare our results with the results obtained elsewhere.

Using our own experience and the Danish guidelines, we have revised the method for measuring the noise emission from large-calibre weapons as in Appendix 2.

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Appendix 1 1(2)

Table A1. Noise emission values for different directions around the weapon or expolsive, as corrected for ground and weather conditions

Weapon	Angle		Sound level, dB				
	o	n	LCpeak	LCE1s	LCI	LAI	LAE1s
95B	0	5	156	127	139	135	121
	45	5	146	128	138	125	113
	90	5	150	127	139	124	113
	135	5	157	136	139	129	120
	180	5	159	135	150	135	122
23AAC	0	5	141	115	127	120	107
	45	5	137	112	125	117	105
	90	5	141	111	124	118	106
	135	5	133	108	120	113	100
	180	5	128	104	117	110	98
120M	0	5	149	127	139	122	114
	45	5	151	129	142	125	113
	90	5	147	125	138	118	107
	135	5	149	127	140	121	110
	180	5	138	122	133	120	101
155C	0	5	163	136	147	146	132
	45	5	148	134	139	126	115
	90	5	150	138	141	126	116
	135	5	156	140	149	132	120
	180	5	157	137	145	132	121
1kg TNT	uncorrected result						
	0	1-2	153	131	144	126	113
	45	1-2	152	130	143	126	112
	90	1-2	150	129	141	123	111
	135	1-2	146	125	138	121	108
	180	1-2	155	129	142	121	118

Table A2. Frequency emission of some weapons ($L_{okt\ 1\ s}$*, dB) at a distance of 100 m*

		Frequency	Hz									
Weapon	Angle	16	32	63	125	250	500	1 k	2 k	4 k	8 k	A
23AAC	0	76	95	105	107	98	97	100	94	90	85	103
	45	90	99	107	107	101	101	99	96	93	89	104
	90	76	90	99	99	94	99	97	95	93	88	103
	135	95	98	102	109	103	96	94	93	91	87	101
	180	84	91	99	102	96	93	93	84	77	71	97
95B	0	100	108	118	117	117	121	115	112	111	106	121
	45	122	128	122	124	116	105	104	103	99	99	115
	90	119	124	124	123	114	115	113	112	108	100	119
	135	134	135	135	126	120	119	115	113	107	105	121
	180	133	137	132	128	123	118	117	116	108	106	121
12.7AAC	0	-	-	-	-	-	-	-	-	-	-	-
	45	63	90	101	106	105	99	98	98	93	86	104
	90	63	84	96	96	88	87	89	85	85	77	94
	135	69	91	97	98	98	96	90	99	81	73	97
	180	65	75	92	97	89	98	93	90	89	83	99
120M	0	116	123	127	120	113	104	104	101	95	91	111
	45	112	125	127	124	113	106	105	103	98	89	113
	90	111	121	122	108	99	104	100	95	89	84	106
	135	109	119	122	113	101	101	100	94	92	85	106
	180	109	119	118	111	105	98	96	93	91	81	105
155C	0	133	134	125	127	128	134	127	124	119	118	133
	45	130	124	124	120	118	113	108	106	103	98	115
	90	126	124	125	118	110	106	107	108	104	93	113
	135	127	134	130	125	120	117	114	112	110	106	120
	180	120	128	126	128	121	120	117	115	111	107	122
1kg TNT	0	117	127	129	126	120	112	110	108	101	96	113
	45	115	125	127	121	118	108	105	104	100	95	112
	90	116	126	128	115	110	115	110	105	104	98	111
	135	112	122	123	119	111	108	108	100	99	95	108
	180	116	126	127	122	117	111	109	106	103	96	118

Appendix 2

MEASUREMENT OF NOISE EMISSION OF LARGE-CALIBRE WEAPONS

1. General

Application area: calibres 12.7-203 mm

The noise should be measured in training areas by the following methods, and especially the following conditions must be considered:
1) suitability of the measurement area
2) noise emission variation for calibres 12.7-203 mm
3) measurement distance 100 m; preferably the peak levels should not be more than 165 dB, the waveforms and the lowest frequencies should be well formed (2-3 wavelengths for 16 Hz; this means 65 m). Sound refections should be minimum.

2. Measurement methods

1. Measurements should be made on 300x300 m of flat terrain without any reflecting obstacles that can influence the measured sound (the distance between the direct and reflected sound being more than 50 m).
2. The weapon should be situated in the middle of the area, and the elevation angle should be the smallest used angle.
3. The measurement points should be situated at a distance of 100 m from the muzzle of the weapons at angles of 0, 45, 90, 135, 180, 225, 270 and 315 degrees from the shooting direction. Safety considerations can limit the use of some measurement sites. However, with automatic measurement systems this problem can be avoided.
4. The microphone should be fixed to a tripod at the height of 1.5 m from the ground so that the axes of the microphone are situated in a 90° angle in reference to the spreading sound wave.
5. The measurement system should have a linear frequency response of ±1 dB in the frequency range of 10 Hz - 10 kHz. The measurement system should be calibrated before and after the measurements.
6. The weather should be dry and the wind velocity should be less than 10 m/s when measured at a height of 2 m.
7. Results: The measurements should be made as a series of 5 consecutive shots followed by a reference explosion at the site of the muzzle. The reference explosion should be 0.1-1.0 kg of TNT or a similar explosive. The sound measurements should be analysed (hit sound excluded) as linear 1-second octave band levels in the range of 16 Hz - 8 kHz. The average values should be corrected to free-field values for which ground irregularities and directional and weather parameters have been taken into consideration (according to the reference explosion). Theoretical values can be used in calculations.
8. The flight noise can be measured if necessary. If measured, the height of the microphone should be 3 m from the ground at a distance of 100 m or more from the shooting site. The microphone distance from the flying projectile should be 2-3 wavelengths (for 250 Hz the distance should be more than 5 m). The axis of the microphone should be in a 90° angle in reference to the shooting direction. If the flight noise is not measured, theoretical values can be used in calculations.

Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Structured approach of lfn-complaints in the Rotterdam region (The Netherlands)

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Summary

In the working area of the DCMR Environmental Protection Agency (EPA) an increasing number of people registered complaints because of low frequency sound (lfs). A 'Protocol of low frequency sound' for use in the Rotterdam-area has been developed. The purpose of the approach on lfs is threefold: (1) to offer the several organisations involved a handle to work with, in order to clarify the nature of the lfs-complaints and structure them in a procedure; (2) to register the experiences with lfs; (3) to possibly develop the policy on lfs.

Conclusions are the following. (a) The indications lead us to assume that lfs is a growing problem. (b) If the source is not found directly there are complex factors contributing to the lfs-annoyance. (c) Those whose quality of life and health is threatened by lfs need help. (d) The introduced system is a good start. (e) Periodic modification should lead to an improvement regarding efficiency. (f) Conditional is a consistent, well-equipped and well-balanced team of people with experience in handling lfs-complaints. (g) To improve the approach it is worthwhile gathering information from complaint handlers elsewhere.

Framework

I intentionally use the word 'sound' because most of the complainants do not use the word 'noise'. So: lfs instead of lfn. This paper clarifies the backgrounds, the systems used with the protocol, and gives a report of the experiences and a look in the future.

The Rotterdam region (Rijnmond) and its acoustic climate. Figures between brackets: in comparison with the Netherlands. Rijnmond is about 2700 km2 (3%), with 1,2 million inhabitants (7%), about 25,000 companies, 200 industrialised sites, 30% of the inhabitants are noise annoyed. There are 18 municipalities of the Rotterdam region. Noise is coming from different sources: traffic (road, rail, water, air) and main sites (factories/harbours).
The Environmental Protection Agency (EPA; in dutch: DCMR) counts about 450 employees. One of the responsibilities are the registration and investigation of complaints, reports and incidents. Specialists are on duty 24 hours as telephone operator and field-inspector. Most of their incoming information is past on to the enforcement-sections. They catalogue the information (in most cases the next day) and arrange follow-up proceedings. The follow-up can consist of a visit to both the companies responsible for the noise annoyance and the complainants. Reports are made of all the activities following a complaint and this is added to the system MIRR [EPA97].

Lfs-history in the Netherlands, especially in the Rotterdam region. Lfs-annoyance is not predicted by the A-weighted levels [VRO, Per]). But effect of those investigations in legislation: none; as the aspect was not important enough in relation to other environmental problems. Since then, Justice sees the lfs problem as a case with *'probable special sensitivity of the receiver'* which means that aggrieved conditions can not (yet) be linked to a licence.

In 1995 and 1996, national meetings of the 'interdisciplinary panel lfs' took place, based on experiences of the Monitoring Network for Health and Environment (a non-governmental organisation of citizens/volunteers). Product: a bundle of 125 pieces of work [MGM96]. Several members of the panel have published their summaries.

In 1997, EPA was host for a national lfs-workshop [NSG97]. This was the starting point for a dutch guideline on lfs. In the same period questions are asked in the Dutch parliament by persistent lfs complainants. Together with MHS (the Environmental Health Department of the *Municipal Health Service*, in dutch: GGD/MMk), supported by the municipality of Rotterdam, EPA started a ad-hoc co-operation to handle the lfs-complaints. Afterwards the City of Rotterdam orders EPA officially to handle lfs-complaints and to gather knowledge.

In the meantime, EPA participates in national lfs-studies for health symptoms, indoor environment. Result: the NSG-Guideline [NSG99].

In November 1999, a start is made with the establishment of a Dutch platform of approximately 60 lfs-sufferers.

Earlier, in december 1998, the EPA-protocol *'handling of lfs-complaints in the Rijnmond-region'* was completed. The lfs-complaints persisted, sometimes accompanied with serious health - and social problems while similar difficulties were recognised in the rest of the Netherlands. Now we have experienced it and this contribution is a clarification of it.

Reasons to deal with lfs-complaints. These are the following.

More attention to the effect on the environment of nuisance [e.g. MGM99].

Social-economical motivation

- A district turns into a poor district when people with higher income are leaving the area. If people are leaving because of (lfs-)pollution, it is bad advertising!
- Health complaints occur after a certain period of time. Waiting for epidemiological results is a waste of time.
- To prevent mentally exhausting juridical procedures.

Social interest

- Sufferers who cannot find an ear for their problems, will seek medical help.
- Paying special attention to lfs-complainants, reduces their feeling of isolation.

Aid

- Minimise insecurity, dissatisfaction and fear of the sufferers.
- Complainants get peace of mind, feeling their problem is seriously handled.

Acoustic climate

- From 1980 the autonomical increase of LAeq has stopped. However, the growing social activities within society are blocking things. Other kinds of noise pollution such as that caused by Lmax, Lfs and as a result of a growing number 'special events' are going to play a bigger role.
- Complaints are indicators. In general: the higher the quantity of complaints, the better the quality of the indicator.
- Raising of consciousness regarding lfs in those who are responsible for sources of sound, and civil policy makers as well.

Spatial planning

. Most noise-problems are in fact environmental planning-problems. Keeping a distance can reduce the problem.

. Concern about the growing use of time and land with noisy activities.

Dealing with lfs-complaints

The EPA-Protocol 'Approach of lfs-complaints'. The number of times that most of the acoustical or social workers come into contact with complaints arising from lfs is in fact minimal. In those cases they need support: a protocol.

Parties involved. The complaints possibly related to lfs come in through different channels, so it is probable that more than one person handles the problem.

- Environmental Protection Agency Rijnmond: complaint-centre employee, enforcement co-ordinator, co-ordinator and manager section Noise. There are 6 EPA-enforcement departments, most of them divided into 2 groups.
- Environmental Health Department of the Municipal Health Service (MHS). There are 4 MHS's in the working area 'Rijnmond' of the EPA.
- Police: interim agents (reporters), environmental co-ordinator.
- Community or province (especially in case of written complaints): handling manager. In the working area of the EPA are 18 municipalities. The municipality of Rotterdam is divided into 10 parts, each with certain independence.
- Housing association: managing employee, caretaker, social worker. There are many of them. An enormous amount of reorganising and merging is going on.
- Monitoring Network for Health and Environment: the provincial agent.
- Dutch Noise Annoyance Foundation (NSG): information-agent.

The collaboration with the Municipal Health Service (MHS, psychological and social aspects) and EPA (technical aspects and management) is part of that protocol, together with a streamlining between the different branches of the EPA.

Possible steps to take. The course of action a complainant usually follows: EPA-complaint centre, one of enforcement inspectors, assistant section Noise. That section will contact one of the departments of the MHS's in the area.
The protocol guides the different partners in the process of assistance. The protocol is not a plan, but a description of experiences until 1998. It is also not a blueprint, but a guide. To find lfs-sources, the EPA-protocol may help, but it is does not specify methods by which to identify them.

Ending a case. It depends upon the degree of involvement whether EPA or MHS end a procedure on their one. Examples of such cases are: source found (EPA starts negociations with the one who is responsible), or a sufferer is a confused persoon (MHS guides to another kind of help). In many cases EPA and MHS deliberate. Examples of reasons to end: the measured soundlevels are extremely low, to find a specific source would take very much effort, there are no possibilities to reduce the sound (e.g. traffic), in simular cases there is no prospect, lfs is one of the (many) problems of the compliant, but not one of the important ones, the compliant refuses (further) co-operation or wants to sell his house.

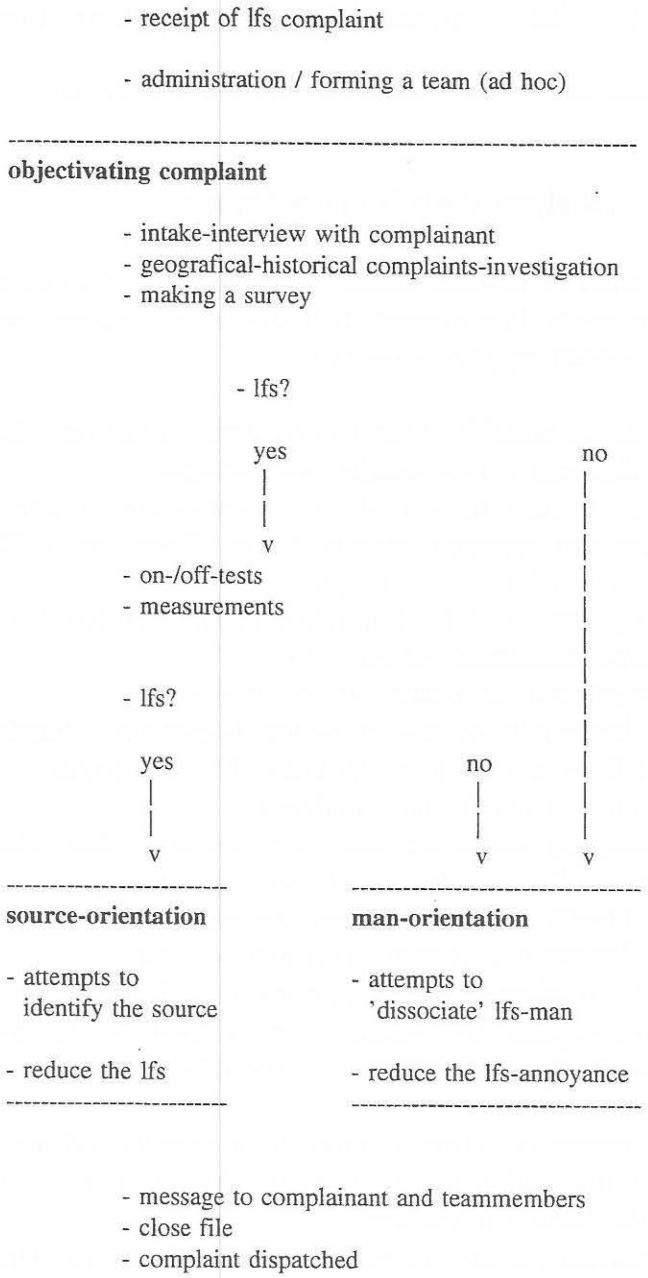

Figure 1: Main outline of the Protocol 'Dealing with lfs-complaints'.

Other aids besides the Protocol. The protocol is a good backing, but more aid is welcome. We developed them.

Forms. Several of them support the procedure as a help to gather information (about situation and circumstances) for filing.
* The one-page communication-form. Every involved party gets a copy of a communication-form, to enable them to see in what constellation is worked and who has to be informed. The form tells the complaint, e-mail adresses, telephonenumbers/faxnumbers and the adresses of all parties.

* The four questionnaires A, B, C and D give a clear picture of the situation. Form 'A focusses the basic cicumstances. When the EPA-inspector pays the informant a visit after he has investigated the environment 'B is used. Form 'C focusses the acoustical aspects. Form 'D is personal, meant for the MHS-assistent.

Files of complaints, factories and acoustic climate. To start the process the EPA-complaint centre does geografic-historical investigiation. The registers of all complaints enables to find similarities. The EPA also has the vast system 'MIRR' [EPA97] in which most of the information about institutes is filed. It is a help to find sources of noise. The section Noise has rough indications of the acoustic climate of most of the dwellings and what kind of noise (traffic, airport, factories) is dominant. But field research is always nescessary, the information mentioned above is just a help.

Complaint following system (cfs) on lfs. About two years ago, the growing number of complaints to handle, where too many for ones memory, so I constructed a simple system to keep those who are involved informed. Administrated: name and place of informant/complainant, dates of complaining, first inventory (e.g. house call), intake MHS date of measurements and report, case-code, providing of the evaluationforms. The dates immediately give a survey of the time passing through. The characters of the case-code are the entrance to a subsytem, a log, in which the main points of the process are kept.
That cfs forces the user to keep it up to date. Otherwise the consequence will be that one has to ask around and to search through files. The cfs contains 4 categories: A = active, processing (34), W = waiting, new facts or a sign from the complainant (9), P = predicted (3), X = finished (66). The figures between brackets are the numbers of February 2000. In the year 1999 the section Noise handled about 40 cases. In a quarter of them measurements have taken place. From the lfs-complaints reported through the complaint centre, about a half of them will be put through to the section Noise. Those are inserted in cfs and probably the most difficult ones.

Measurements. The preparations for measuring and the making of the reports take a lot of time. We only do this if necessary. Sometimes, for certain in cases in which measurements are combined with on-/offtests, a measuring-scheme is made.
We are reserved with semi-automatic measurements made by the complainer. The circumstances and the fact what exactly should be measured are not always clear. If possible we take much time for the measurements and sample exlusively the wished sounds. In the cases that after the event has to be disturbances traced and sifted. We experienced that it takes much more time.
We use a list to memorize what machines should put off in the house, and also to use what to put on again afterwards (refrigerator, alarms, heathingsystem-pump etc.).
The measurements will take place at the time that the complainant hears the sound best, so very often at night and on the complainer's bedroom pillow. But to gather more information, the measurements also take place in other places in the house.

The files of complainants. The section Noise of the EPA makes workfiles, titled on (main)complainant's name. The workfiles are ordened geografical. Official aim: because the way EPA works is geographical. Acoustical aim: to recognize equal sources and cases in the neighbourhood (even if the time between two cases is over more years).

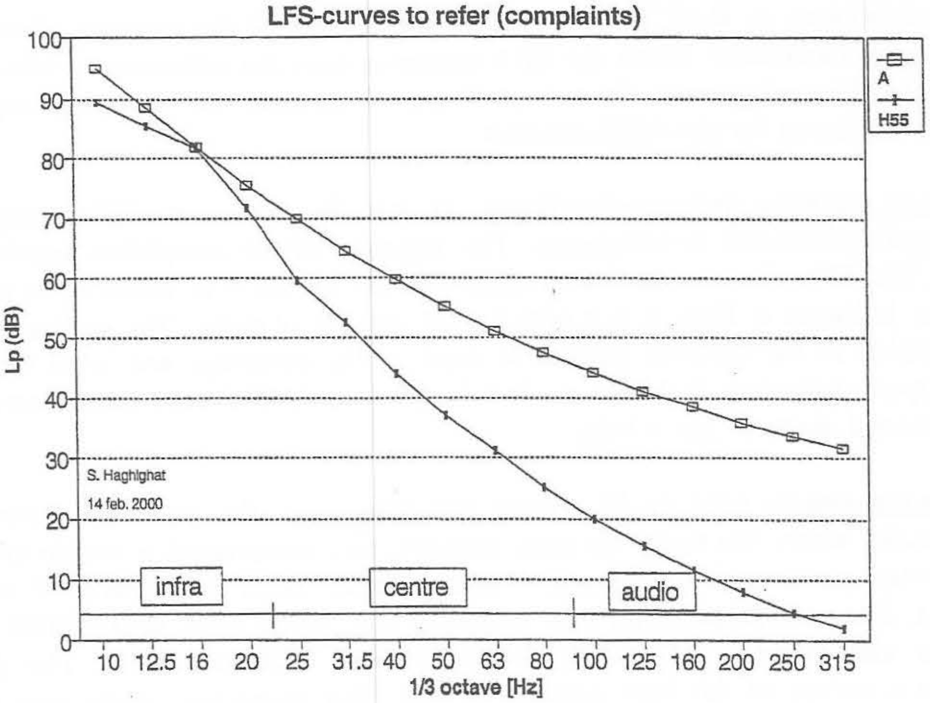

Figure 2: Checking of lfs measurement results (Protocol curves).

Legend: see figure 3

Communication. We developed several ways to communicate with the people dealing with the lfs-problems: complainants, EPA + MHS, other reliefworkers.

With complainants. Ambition: sincerity, honesty, and - last but not least - clarity.

In many cases there is dialogue with MHS. Sometimes it's found that there are personal problems not caused by lfs. To draw extra attention to the sub-problem 'lfs and to enlarge it that way is not tactical or decent. That is a reason not to end the complaint handling with a letter, written by EPA and/or MHS, in which is explained why the investigations are stopped and what can be done next or instead.

In 1999 a brochure is made and distributed through town halls, libraries, pharmacies, hospitals and medical doctors in the Rotterdam-region.

Between EPA and MHS. The EPA-section Noise and the Environmental Health Department of the MHS have almost daily contacts to deal with one or more lfs-cases. To discuss general aspects, lines of policy, changes in the way we work and to keep each other well-informed, the lfs assistents of the Noise-section and assistents of MHS's have periodical meetings on lfs and meet about three times a year.

With other reliefworkers. The experiences, novities, results of research in literature, information and possible ways to prevent lfs or to reduce the nuisance, and the quantitative condition of lfs case-handling are gathered in quarterly reports. It is a way of sharing knowledge, to keep people informed and to use with the general quarterly reports made by EPA.

Results

Although in acoustical view not in many cases is given a solution, there is quite a fulfilling of the aimes formulated under 'Reasons to deal with lfs- complaints'.

The annoyed, the society and the EPA. Nowadays there is a new attitude: showing respect. That the attitude, the experiences and the knowledge of the sufferers is an important part in case-handling. It gives them back their self-confidence and enables them to relativate the situation. The EPA really works for the empowerment of citizens. We give them our expert support.
The intern co-operation at EPA has improved; other authorities learned where to find us.

Experiences. Thanks to the intensive way of dealing with the lfs-problems many and various experiences are made [e.g. Slo99]. The most importants are the following.

Sources of noise.

- Many times no (evident) sources were found. Further investigation is not likely.
- Most of the cases don't have a specific 'grand source.

Measurements.

- Important to ascertain the complaint are tests in which the suspected source is set on and off. The complainant has to tell the investigator when and what differences are heard. Other simple aids to get any impressure about the hearing of the complainant are whispering speaking and watch reactions, turning the volumeknob of a television or tuner in 'rustling', using soundgenerators.
- In most cases analyses of and up 40 Hz third-octaveband is enough. Maybe that in future a simple rough quick scan, in octaves, starting with 31 Hz octave, under ideal circumstances, will give enough information to make further decisions.
- Until now, we judged vibration-measurements necessarly in only three lfs-cases.

Acoustic lfs-references (indoors, at night).

- The (normal-used) 25 dB(A)-limit, is not sufficient to recognize complaints.
- Nor is the general rule 'lfs, if L(C) - L(A) > 20 dB (German)' [DIN]. If that indicator is overruled, then the lfs-nuisance is almost certain.
- In cases the investigators also experienced some of the lfs, the A-weighted level was most of the times 21 dB(A) or higher.
- There is no indication that many cases are dealing with audible tonal sound [PSl].
- The threshold-curves do not explain the lfs-nuisance felt by all the sufferers, but is a help in comparing the measurement results.
- Telling the complainer the percentage of people that can hear 'his or her measured sounds, is a support.

Attitude in way of working.

- Involve citizens in the process of watching has the advantage that the dealing-process goes faster. Besides such citizens are keeping you awake.
- Do not trust on certainties of the sufferer, nor on premisses of yourself.
- Work step by step.
- Document: for own good, authorities, other parties involved and sufferers.
- Although the amounts are too small for statistic use, it's obvious that the reporting of complaints until now is unequal. Per quarter, in which the months of May + June + July are the first quarter, the relation is 6 : 3 : 2 : 3.
- We, EPA-assistents, are inclined to forget the step 'calling in MHS'. Very often, in cases we made that mistake and then it needs to be corrected....

Status of 'assistence' (reliefworker).

- Be prepared for resistance. Dealing with lfs-complainants might be seen as dealing with 'loosers' and with non-kwantificable results.
- The lfs-dealing principle of openness makes that there are many and unexpected contacts with both complainants and collegeus. Take enough time to communicate, every day again.
- In many cases there is a combination of aspects complicating the investigation.

Lfs-sufferers.

- Sufferers are not different from the ordinary-Hollander. Mostly good-hearing, but alerte people; women and elderly persons are over-representated. [compare MGM96]
- The EPA-lfs files gives following results: (a) average age 55; half of them living alone, (b) 2/3 female, 1/3 male (exactly in accordance of [Gie98]). But: notice that a small enquete in the complaint centre of EPA learns that of <u>all</u> kind of complaints coming in (20,000/year) also 70% is female and the estimated average age is 55 as well! So in one way the notion of lfs-complainants is not very special.
- The impression is that the wishes of the lfs-sufferers about quiete are high. They seem to respect and to like silence; in many cases there is a 'lack of indoor sound.
- I confirm the results of other investigators [e.g. Per] that in many cases there is a relation between the personal expression of susceptibility and the reactions to lfs.

The public spread of information about lfs.

- Due to the complexity of complaint handling and still new experiences, it is useful to keep the used tools like questionnaires, letters and procedures, up to date.
- In several cases EPA and MHS 'took a risk' and asked publically for help. There were no floods of complaints coming towards us.

Look in the future

Expectations. Related to the handling of lfs-complaints, gradual changes will take place.

- In 15 years 1/3 (1/2 in all Holland) of the Rotterdam inhabitants will be 55+ years of age. At this moment most of the lfs-complainants are in this agegroup.
- The mutual use of buildings for 'industrial' and 'living' purposes is increasing. Ventilation system, heating system, air-conditioning etcetera can cause problems.
- At the moment only 3% of Dutch homes is provided with climate control installations. Those are sources of lfs. The numbers will grow.
- Due to the lack of building space more underground infrastructure is being developed. Vibrations caused by traffic result in lfs via the foundations of residential buildings.
- Within a few years in the Netherlands there will be a new legislation for noise and urban planning [Wig97, Wig98]. The municipalities will then have the right to more independend regarding the setting of noise level limits. Due to the prohibitive cost of space this will in some cases result in excessive noise taxation. Particularly lfs.

To achieve a higher returnof complaint handlers in relation to the resources used, a shortened procedure is in some cases required. The original procedure will only be adhered to if: 1) the informant can substantiate the complaint (eg. witness testimony), or if a quick-scan by one of the researchers of the complaint provides a clear cause in the first instant. 2) a justifiable request by a member of social assistance agency is received (from housing association to general practitioner).

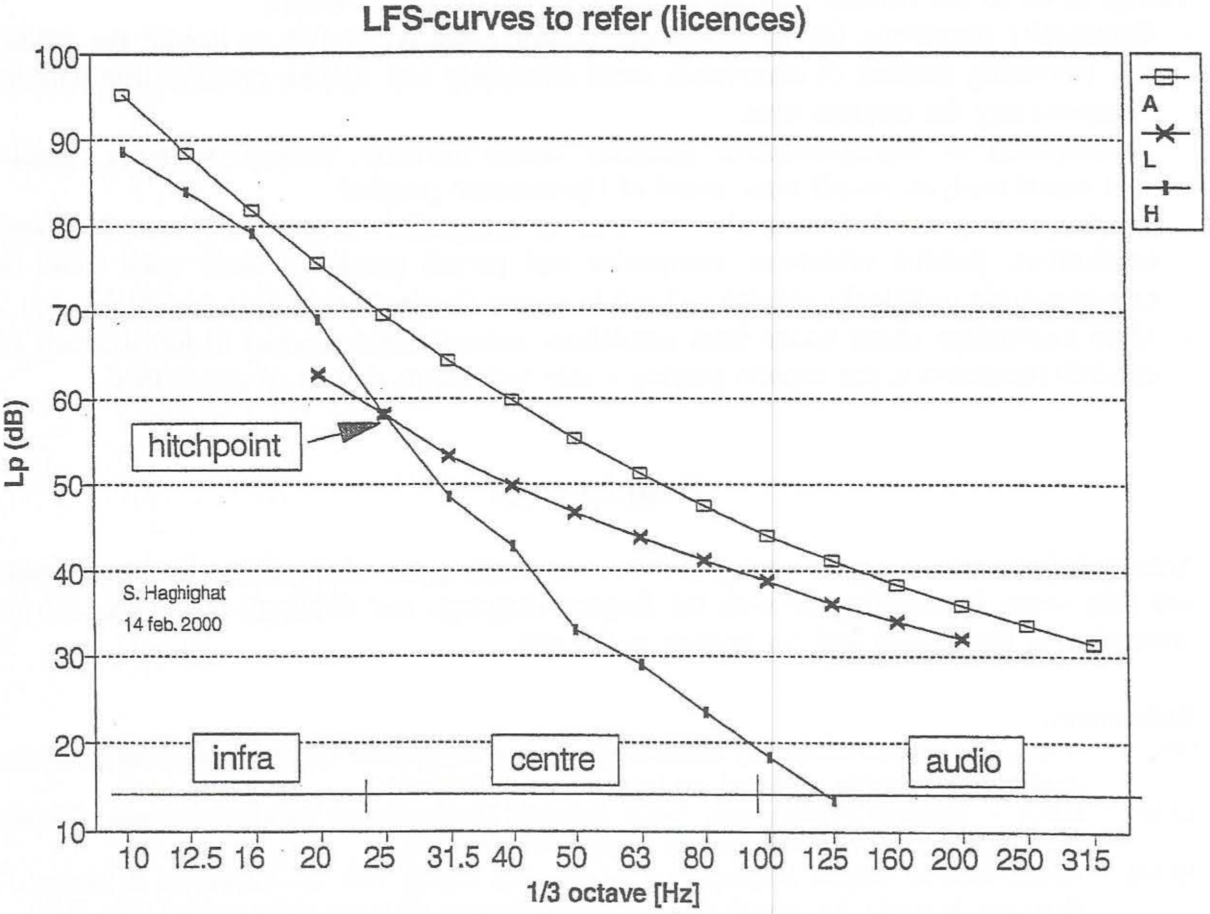

Figure 3: Proposal to use in licences (P. Sloven. 2.2.2000, to be discussed).

- *Just in the most aggravating circumstances.*
- *For the present: situations within homes at night.*
- *More are less continuous and 'normal lfs, limiting extra annoyance (tonal, banging characteristics, combination with tangible vibrations).*
- *To be judged more severe in case of combination with tangible vibrations and in case of lfs with a clear banging character.*

Above the x-axis the parts of the lfs-frequencies.
The y-axis: equivalent unweighted 1/3 octave band sound levels.

Lfs-curves intended for use by permit granters [Slo00] and the EPA-Protocol.
A = 25 dB(A); all sound-energy concentrated in one 1/3-octave.
L = Lfs-limit. Above that curve there is excessive annoyance. To use as license-limit from 25 Hz.
H = HTL5 = Hearing Thresh-hold Level that can be experienced by 5% of the 'average Dutch. To use as license-limit up to 25 Hz.
H55 (figure 2) = Hearing threshold level to be heard by 5% of the most important groupe of complainants: those who are aged about 55 years. [Pas].

Things to do in the future. To improve the approach there are wishes ....

- Continually improving the anamnese on lfs will make it possible to handle the gradually increasing number of complaints more efficiently and shorten process-time without compromising the original aims.
- Development of source-detection methods: sound intensity, microphone-array, intelligent signal analyse, on-off-tests, panel of lfg-sensitive people?
- To find a way to deal with licenses that is acceptable to most of those involved. (authorities, judicial reviewers, companies and permit granters). Such rules must be communicable (relatively simple) and not to severe (business activities possible).
- More knowledge about house-front insulation, noise-transfer, spread in thresh-holds of audibility/sensitivity, the aspects playing a role serotonine, degree of annoyance.

Supplements

Acknowledgements. I express my gratitude to my colleagues of the EPA: José van Reede and Siân Jones for helping me with the English language and Shahram Haghighat for his production of the figures and his advices in the past.

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Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Assessment of noise with low frequency line spectra – practical cases

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Summary

Many small power plants have been built in Denmark the latest years. These plants are often situated near dwellings giving rise to complaints about annoyance of low frequency noise and vibrations indoors. Normally the annoying low frequency noise is in the frequency range 10-200 Hz. Since it is created by combustion engines the noise has a line spectrum. In Denmark the A-weighted total level in the frequency range 10-160 Hz $L_{pA,LF}$ is used for assessment and legislation about low frequency noise exposure in dwellings. From our experience solving practical low frequency noise and vibration problems $L_{pA,LF}$ seems to overestimate the annoyance of very low frequency noise whereas noise with the major spectral content near 160 Hz seems to be underestimated. This problem is discussed based on our experience.

Introduction

The latest years many small thermal power plants have been built in Denmark replacing larger central power plants. This decentralisation has caused many power plants to be situated close to dwellings. The short distance to the neighbours call for a very strict engineering in the design of the power plants in order to avoid low frequency noise and vibration disturbance. As consulting engineers within noise and vibration control our company has solved several problems where one or more factors in the design of the power plant has caused low frequency noise and vibration annoyance of the neighbours.

In cases where neighbours to power plants are annoyed by low frequency noise, the problem is normally only experienced indoors. Sometimes the neighbours can be annoyed indoors even if the power plant complies with the normal external A-weighted noise exposure demands. This is due to the fact that low frequency noise can be transmitted to the neighbour houses as structure-borne sound via the ground or the heating pipe connection. The noise is then radiated from the floor, walls and ceiling of the house. Differences in natural frequencies of the building elements can cause quite different indoor noise levels in two different houses even at the same distance of the power plant.

In order to handle the above-mentioned problem the Danish Environmental Protection Agency (DEPA) has in Miljøstyrelsen[1] specified techniques for indoor measurements of low frequency noise and vibrations together with a set of recommended limit values. The parameters to measure and the recommended limits are seen in Table 1.

Based on the experience of our company noise and vibrations from power plants most often give problems complying with the low frequency noise level $L_{pA,LF}$. Therefore, the present paper discusses $L_{pA,LF}$ and its correlation with the subjective evaluation of the noise.

Parameter	**Technical description**	**Recommended limit**
Low frequency sound, $L_{pA,LF}$	A-weighted sound pressure level, 10-160 Hz	20 dB re. 20 µPa
Infra sound, L_{pG}	G-weighted sound pressure level, 1-20 Hz	85 dB re. 20 µPa
Low frequency vibrations, L_{aw}	KB-weighted acceleration level, 1-80 Hz	75 dB re. 1 µm/s^2

Table 1: Parameters and recommended limits for indoor noise and vibration levels stated by the Danish Environmetal Protection Agency.

Typical indoor noise spectra

Often the power plants are powered by one or more diesel or natural gas driven 12-20 cylinder engines running 500-1500 rpm. The noise and vibration "finger prints" from such engines are characterised by a line spectrum. The basic frequency of this harmonic line spectrum is determined by the engine rotation speed. In addition, large noise levels can be expected at the engine firing frequency which is determined also from the number of cylinders.

Figure 1 shows an example of the vibration spectrum measured on a V18 cylinder gas engine running 1000 rpm. As seen the basic frequency in the harmonic spectrum is 8,3 Hz.

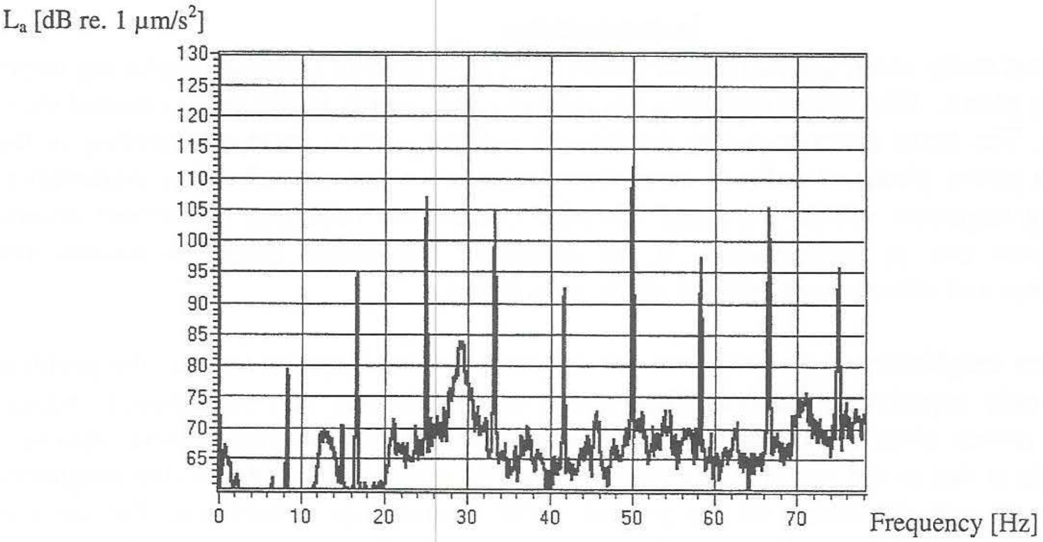

Figure 1: Narrow band spectrum of vibration level measured on a V18 cylinder gas engine running 1000 rpm.

Low frequency noise can be transmitted from the power plant as air-borne or structure-borne sound. The typical air-borne transmission paths are from the exhaust gas outlet, the engine cell ventilation or radiation from the walls and roof of the power plant. Structure-borne noise can be transmitted either via the ground or via the heating pipe connection to the power plant.

Figure 2 shows the low frequency noise measured in the dwelling near the power plant with the engine from Figure 1 running. The characteristic pure tones from Figure 1 are easily recognised and the resulting $L_{pA,LF}$ value of 23 dB is above the recommended limit. Please note that the fundamental frequency 8,3 Hz is not seen since the A,LF-weighting is not specified below 10 Hz.

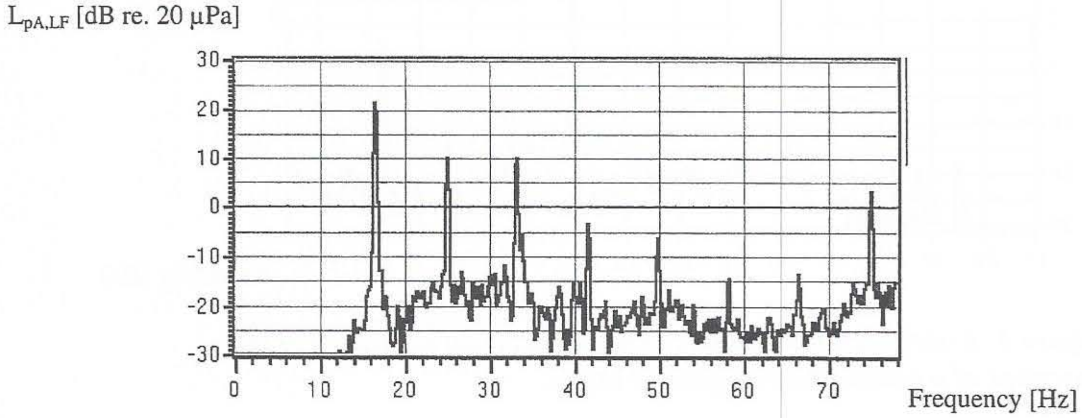

Figure 2: A-weighted low frequency noise spectrum measured in the living room of a power plant neighbour.

The subjective response to the noise in Figure 2 with a $L_{pA,LF}$ level of 23 dB is that it is a very deep noise, clearly audible, but still at a very low level. However, one person living in the house felt highly annoyed. Reduction of the transmitted vibrations by improving the elastic suspension of the engine resulted in the spectrum seen in Figure 3.

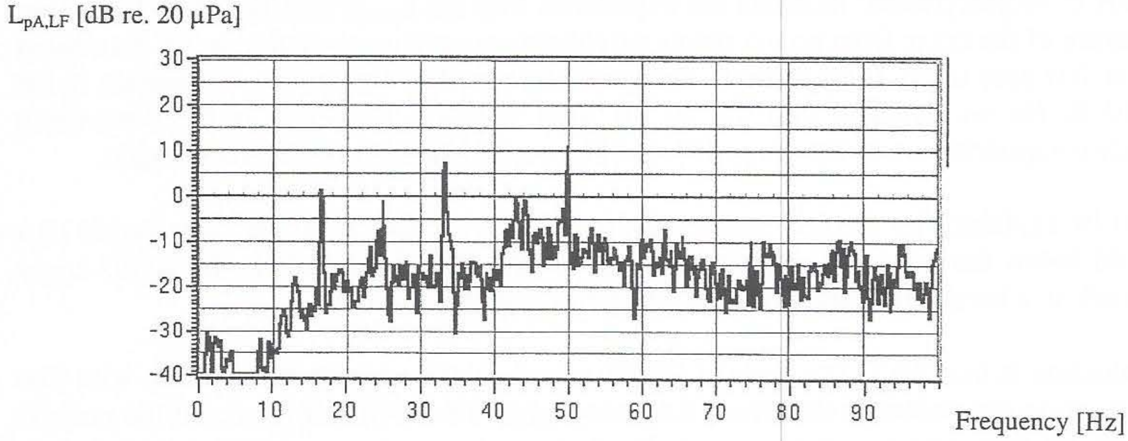

Figure 3: Noise spectrum measured in the same position as in Figure 2 but after improvement of the elastic engine suspension.

As seen especially the dominating 16,7 Hz tone was considerably reduced. The $L_{pA,LF}$ value was reduced to 15 dB. The subjective response to the resulting noise is that it is hardly audible and the annoyed person was satisfied.

Another example of indoor noise is seen in Figure 4. The A-weighted noise spectrum measured in the position in the basement with the highest level. As seen the noise is clearly dominated by a 100 Hz tone and the $L_{pA,LF}$ value is 21 dB. However, since the average value of all measurement positions in the room was below 20 dB the $L_{pA,LF}$ limit was not exceeded.

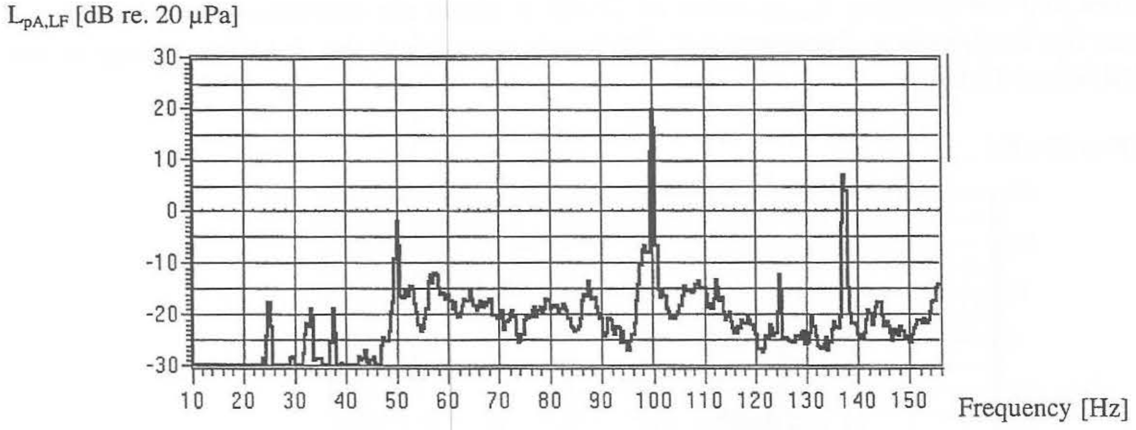

Figure 4: A-weighted low frequency noise spectrum measured in the basement of a power plant neighbour house.

The subjective response to the noise in Figure 4 was a clearly audible, irritating humming noise which also caused complaints from the occupier of the house. The problem was structure-borne noise from the power plant transmitted to the neighbour via the heating pipe connection in the basement. Careful vibration isolation of the piping at the power plant solved the problem and the neighbour became satisfied.

Conclusion

The two examples described above with noise measured according to the guidelines given by the DEPA in Miljøstyrelsen[1] illustrate our experience with the $L_{pA,LF}$ and the 20 dB limit. Due to the nature of the noise from power plants neighbours are often exposed to noise dominated by one or few pure tones. If the noise is dominated by very low frequency components in the range 10-30 Hz we evaluate that the 20 dB limit is strict. However, if the dominating frequency components are in the range 100-160 Hz we evaluate that the 20 dB is vague.

This can be explained by the fact that at 20 Hz the $L_{pA,LF}$ value of 20 dB corresponds to a level 3 dB below the hearing threshold described in ISO 389-7[2]. At 160 Hz the 20 dB $L_{pA,LF}$ corresponds to a level 20 dB above the ISO 389-7[2] threshold.

Our evaluation is that the $L_{pA,LF}$ limit of 20 dB may be an acceptable compromise with low frequency noise distributed in the whole frequency range 10-160 Hz. However, if the noise is dominated by pure tones or very narrow band noise, $L_{pA,LF}$ does not give a satisfactory correlation with the subjective effect of the noise. Therefore, more knowledge should be collected for creation of an additional quantification method for indoor low frequency noise.

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Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Annoyance from "Inaudible" Infrasound

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Summary

While it is well established that infrasound levels above, or even very close to the threshold of hearing can cause annoyance, there are also reported cases of annoyance arising from levels below the auditory threshold and not readily detected directly. These are cases in which the infrasound either causes rattling of light structures, such as windows and doors, or gives rise to tactile vibrations giving concern for the safety of the building structure. Some case histories are discussed together with available data on criteria.

Introduction

Early studies of the threshold of hearing at infrasonic frequencies concentrate their attention upon auditory perception. Békésy (1936) made an excellent determination of the threshold down to 1 Hz, his main area of interest being the physiology of the hearing process. Later work by Mohr, Cole et al (1965) explored the areas of exposure to whole body infrasound with particular reference to the maximum levels which could be tolerated from the points of view of task performance and possible injury. Further studies were made by Yeowart et al (1976) who investigated aural and whole body exposures and also explored monaural versus binaural stimulation and thresholds for infrasonic noise bands.

The work referred to above, and other studies, demonstrated that the ears are the primary receptor sites for infrasound and showed that for pure tone (sinusoidal) stimulation the sensitivity of the ears falls very rapidly as the frequency is reduced. Whole-body responses occurred at higher sound pressure levels than the aural threshold.

Some cases arise in which infrasonic levels below the normal threshold of audibility can be detected by their indirect effects. In this paper reference will be made to some case histories of this kind.

Case I - Foundry Noise

This arose in a village where a number of residents complained about rattling windows and doors although no low frequency sound was directly audible. The residents were annoyed by the rattling sounds and were also concerned that these might be due to some vibration which could prove damaging to their homes. Investigation showed that the rattling appeared to be due to a 12 Hz tone at a high level with a very pure wave form without detectable harmonics.

Central to the village was a small foundry whose equipment included a shaker table, used to shake sand from castings. The platform measured 3.7 x 3.7m and vibrated at a steady frequency of 12 Hz. The building housing the shaker table was of very open construction with various doors, windows and ventilation holes and was therefore acoustically very transparent. It seemed very likely that this shaker table was the source of the problem and it was therefore investigated in more detail.

At this foundry the casting sand was always recovered for further use and for this reason the shaker table was built over a pit. This arrangement roughly resembles a very large loudspeaker box of about 10 x 4 x 3m. Sound pressure level measurements showed a 12 Hz pure tone of 130 dB above the "vent" of this "loudspeaker". Investigations at the complainants' houses showed levels up to 91 dB spl on their premises. Figure 1 shows the complainants' noise exposure levels in comparison with the binaural hearing threshold. This comparison demonstrates that the complainants' levels were just below the binaural hearing threshold, although they were clearly sufficient to cause rattling .

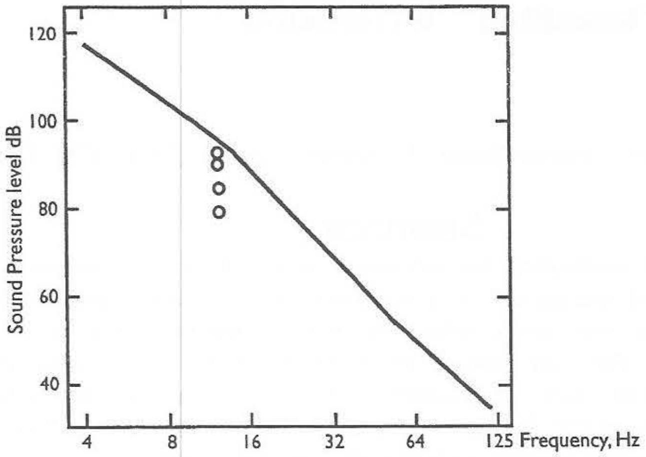

Figure 1: Binaural threshold of hearing and measured noise levels at complainants' houses.

A number of solutions were considered in order to deal with this problem. Enclosure of the shaker table did not appear to be economically feasible, it was too big and would have required large opening/doors for access. Reducing the amplitude of the table vibration or lowering its frequency were both rejected since they would have seriously impaired the table's efficiency. A solution was therefore sought to lower the effectiveness of the table and its associated pit as a sound generator. To do this a 'port' of about 1 x 4m was opened in the side of the shaker table and the flanges at the front and the rear of the table were also taken away. These modifications effectively "short circuited" the table and reduced radiated sound levels. At the sensitive locations where complaints had occurred levels were reduced by 5-6 decibels and this was sufficient to bring the complaints to an end.

Figure 2 shows a sketch of the shaker table with the modification to reduce the infrasonic levels generated.

Case II - Asphalt Plant

Complaints in this case arose from residents living some 200-300m from an asphalt making plant. The complaints were of rumbling noises and what the residents regarded as structural vibration in their homes. Investigations showed that the rumbling was due to noise in the octave bands from 64 Hz upwards at levels above the hearing threshold. Energy in the 32 Hz and lower frequency bands was giving rise to window vibration which could be felt on touching the windows and could be seen by reflected light. This window vibration had given rise to fears for the safety of the buildings since the residents had formed the view that it was evidence of damaging structural vibration.

The source of the noise was traced to a part of the asphalt plant used to dry sand and gravel. The particular piece of equipment consisted of a steel cylinder approximately 15m long and 2m in diameter. This rotated slowly on rollers while vanes on the inside lifted the sand and gravel and thus conveyed it down the cylinder. At the "entry" end of the cylinder a pressure fed oil burner with a heating power of approximately 500 kilowatts forced a very large, roaring flame into the cylinder to heat the air and dry out the contents. The noise arose from this burner.

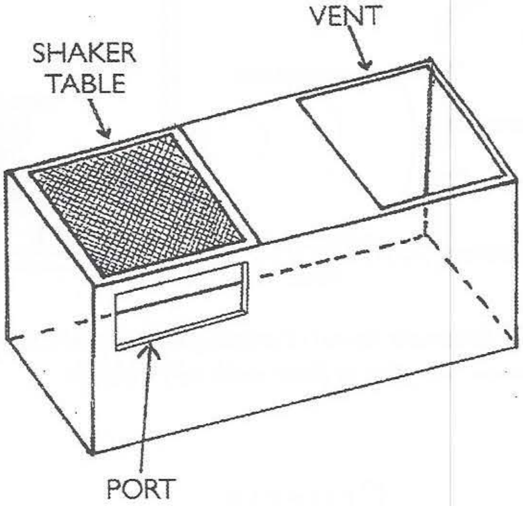

Figure 2: shaker table with modification

A wholly satisfactory answer to the complaints in this case proved difficult to find, the only totally effective proposal being that the entire plant be moved to a less sensitive location, however the residents were much reassured when they understood that the window vibration was only due to infrasound and that there was no structural vibration which might damage the walls and foundations of their houses. The problem had been investigated at the instigation of the Local Authority and it was left to them to deal with the economic and political aspects.

Case III - Flat bed printing press

In this instance residents close to a printing works were complaining of vibration in their homes which they attributed to the printing works separated from them by a road.

Investigation began with vibration measurements in the houses but nothing could be detected. However there was visual and tactile evidence of window movement and some audible perception of a low pitched "thump" happening at 1 pulse per second. This led to the conclusion that the problem arose from low frequency pulses of airborne sound.

Investigations at the printing works found a flat bed printing press which operated once per second in a location close to the wall of the printing works and opposite the complainants' houses. Measurements around the printing press did not show any levels of infrasound which seemed likely to give rise to the effects at the complainants' houses. In order to investigate the matter further vibration measurements were made at the base of the press which showed high levels of vibration at this point. It was also found that the printing press was mounted directly on the concrete floor without resilient mounts and the floor was built on very poor foundations which therefore allowed it to move under the impact of the press. This vibrational motion was then transmitted across the floor to the wall of the building. The resulting movement of the wall generated airborne low frequency sound which travelled across the intervening roadway to the nearby houses. Figure 3 shows the schematic layout of the printing works, the road and the houses.

As a first step in dealing with the problem it was possible to reassure householders that their properties were only subject to airborne infrasound and that there was no risk of damage due to structural vibration. The printing works were advised to remount the press on suitable vibration insulating mounts between the press and an appropriate foundation.

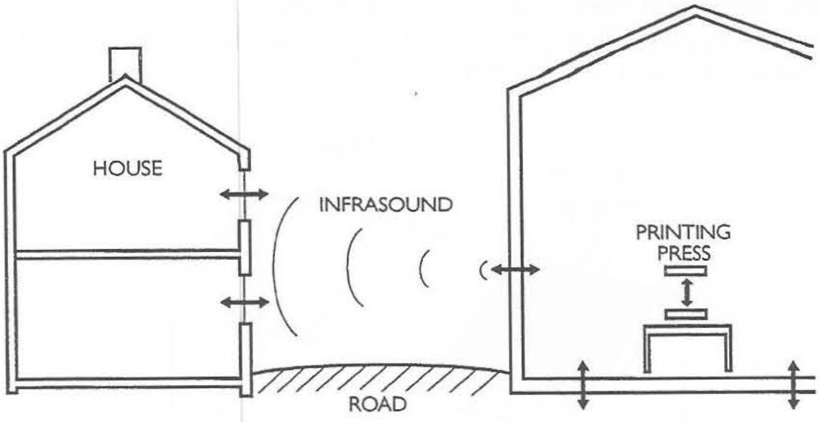

Figure 3: Schematic layout of printing works, road and houses.
⟷ *vibration of floor, walls and windows*

Criteria

Criteria for the type of problem described above are difficult to establish since the noise levels at which structures begin to vibrate and rattle clearly depend on their construction. It is however evident that in some circumstances the "rattling" threshold can be at a lower level than the threshold of audibility.

A "minimum threshold of rattling noise" has been put forward by Yamada (1982) and is set out in Figure 4. This shows the four regions of inaudibility, audibility, rattling and audibility plus rattling. Our own experience would tend to support this criterion.

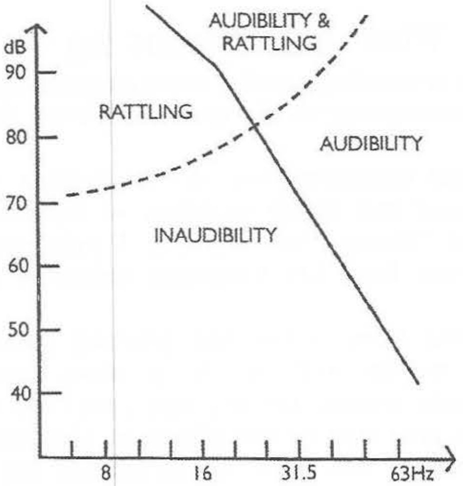

Figure 4: the hearing threshold– full line: and the rattling threshold– broken line (from Yamada, 1982)

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Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

Assessment of vibrations from landbased transport – A new Norwegian standard

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Summary

Protection against vibration nuisance in order to maintain satisfactory conditions during work, sleep, rest and recreation was specified in the Norwegian building regulations in 1997. Problems with soft clay with high water content in densely populated areas cause vibration problems in dwellings from heavy road and rail traffic. A qualified vibration measurement method for transport sources was published as Norwegian standard NS 8176 in 1999. An empirical method for determination of statistical maximum value of velocity or acceleration ($v_{w,95}$ or $a_{w,95}$) and guidelines for assessment of vibrations is introduced and exposure-effect curves presented as a basis for a classification system with four vibration classes in relation to the vibration nuisance.

Introduction

In 1992 several parties involved in vibration problems from landbased transport in Norway initiated a project to find acceptable limits for vibrations in dwellings. The ground in many densely populated areas in Norway consists of soft clay with high water content causing vibration problems in dwellings from heavy road and rail traffic. As a result of this project recommended limit values were presented later on by Brekke and Madshus[2], but the practising of the limits was insufficient as a qualified vibration measurement method for transport sources was lacking. In the same time, protection against vibration nuisance in order to maintain satisfactory vibration conditions during work, sleep, rest and recreation was required in the European Council Directive on construction products. These matters initiated introduction of a new, more functional system for the construction works, the executive work and the control of the building process in the Norwegian building regulations[9,14] in 1997. As a consequence, the work with a new measurement standard, NS 8176[18], started and it was published at the end of 1999. The standard is linked to regulations and guidelines for evaluation of effects of vibrations on human beings in dwellings through the Technical Regulations to the Planning and Building Act 1997[12,14] and health legislation[13].

An experimental method for determination of statistical maximum value of velocity or acceleration ($v_{w,95}$ or $a_{w,95}$) and guidelines for assessment of vibrations based on a large number of measurements in Norway, calculations and statistical analysis of data collected in a database[3,7,8], was introduced. By means of a national vibro-social survey[3,4,5], the vibration values were related to the people's experiences of degrees of nuisance due to vibrations from transport sources. Results from a similar Swedish sociological study made by Öhrström[11] were also assessed. A vibration classification system for buildings based on estimated exposure-effect relationships between human reactions and the statistical maximum velocity or acceleration ($v_{w,95}$ or $a_{w,95}$), was provided in four classes (A, B, C and D).

Measurement method for vibrations from transport

NS 8176[18] introduces an empirical method for measurements for velocity or acceleration from transport sources, and guidance for evaluation of vibrations. The method was tested in a national Round robin study[1] where 14 measurement institutes and companies in Norway participated. Two alternative ways of determining the weighted velocity or acceleration for single passings is presented either by using geophones or accelerometers. One way is to first make measurements with equipment without a weighting filter and then determine the 1/3-octave band values in the frequency range of 1 to 80 Hz. These 1/3-octave band values are then multiplied by weighting factors for combined weighting filters presented in ISO 2631-2[16] and ISO 8041[15]. The other way is to make direct measurements with equipment that has a built-in weighting filter. A time constant of 1 s is used (corresponding to S (*slow*)). The vibrations are to be checked in the three orthogonal directions. Transformations between *weighted* values of velocity and acceleration may be made by using formula $v_w = a_w/35{,}7$.

On floors with carpets or some other soft covering, a tripod metal plate[18,19] can be used to mount the pick-up at the relevant location in such a way that the mounting method has no effect on the measurement results. The vibrations are measured at the position on the floor in the bedroom, work room or living room where the highest values of velocity or acceleration occur. In most cases the vibrations are higher in the vertical direction than in the horizontal direction, and the highest values are usually measured in the middle of the tier of beams or floor that has the longest span.

Values of maximum weighted velocity or acceleration are registered during the time it takes for the relevant motor vehicle, train, underground or tram, etc. to pass. At least 15 individual passings (trains, underground, trams or heavy road vehicles) must be measured at each measurement position. For railroad traffic, minimum 30 % of 15 measured train passings shall be selected from the train type that gives the highest values of weighted velocity or acceleration (most often goods trains). The distribution of the train types shall be representative for the relevant traffic situation at the location in question, and this distribution is used in calculations of the statistical maximum value as described here in the next section, and likewise when more than 15 passings are concerned. For the ordinary road traffic, only vibration values measured from heavy road vehicles with a total weight greater than 3 500 kg, i.e. lorries, busses, dump trucks and similar transport units, shall enter in the calculations of the statistical maximum value. Also, traffic to and from sites for building and civil engineering works is considered.

The measurement results shall be presented both as an average value of the maximum weighted velocity or acceleration ($v_{w,max}$ or $a_{w,max}$), standard deviation (σ) of the maximum weighted velocities or accelerations, and as a statistical maximum velocity or acceleration ($v_{w,95}$ or $a_{w,95}$) at each measurement position. The standard deviation from the mean, σ, of the maximum weighted velocities is calculated by using the formula:

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(v_{\mathrm{w,max},j} - \overline{v_{\mathrm{w,max}}}\right)^2}$$

The statistical maximum value is then calculated as follows:

$$v_{\mathrm{w},95} = \overline{v_{\mathrm{w,max}}} + 1{,}8 \times \sigma$$

This calculation is an approximation, and the formula is based on a log-normal distribution of the measurement data. It is valid when the coefficient of variation is less than 1,0. The value of the statistical maximum velocity or acceleration, determined according to this method, gives 95 % probability that new measurements - and calculations of the statistical maximum value - lie in the range of ± 20% from the first value. The uncertainty in this case is defined as twice the standard deviation, given in percentage of the mean of the statistical maximum value for velocity or acceleration. This uncertainty is reduced by increasing the number of the passings included in the calculation.

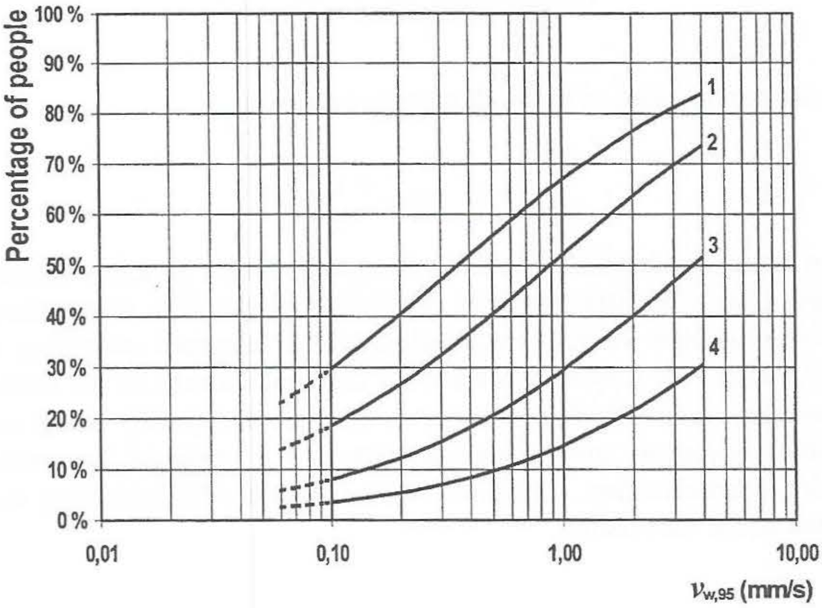
Exposure-effect curves for degree of vibration annoyance

People's reactions to vibrations were studied through a sociological interview study[5,6] along rail and road tracks where it was known that vibrations might exist or existed. The vibration values in respondents dwellings were collected by measuring or using existing measurements along the tracks and calculating the vibration values in the dwellings by using the computer prediction method presented by Madshus *et al.*[7,8], including various input data for the building variables.

A clear relationship between the intensity of vibrations and the human responses was found, thus the human vibration annoyance increases with the increase in vibrations[4,5,6]. This relationship, analysed by using statistical ordinal logit models, was plotted in the form of exposure-effect curves for vibration annoyance, see figure 1. Statistical analysis made by Klæboe[6] showed that the vibration effects from the various sources (road traffic, railway, and underground/tram) were not significantly different at a given vibration exposure. Thus, the exposure-effect curves are the same for these transport sources. Control of variables like age, sex, sociological data, living areas etc. did not show significant differences.

The curves show the average effect of vibrations in the population in their living situation and may not be directly applied to groups that are more sensitive to vibrations, or exposed to various environmental stresses. However, since the investigation is performed as a field study, there is some uncertainty in the population reactions at low vibration values, i.e. close to the perception limits. Due to this uncertainty of the curves below 0,1 mm/s, they have been drawn as dotted lines.

The results show for instance that at 0,3 mm/s about 8 % of the people were highly annoyed which is a used as recommended percentage in the consideration of noise limits. Above 10 % of the persons were highly annoyed due to vibrations in dwellings at a vibration exposure of 0,6 mm/s. At the same vibration value more than 40 % of the persons were annoyed if all the groups, highly, moderately and slightly annoyed, are considered.



Key

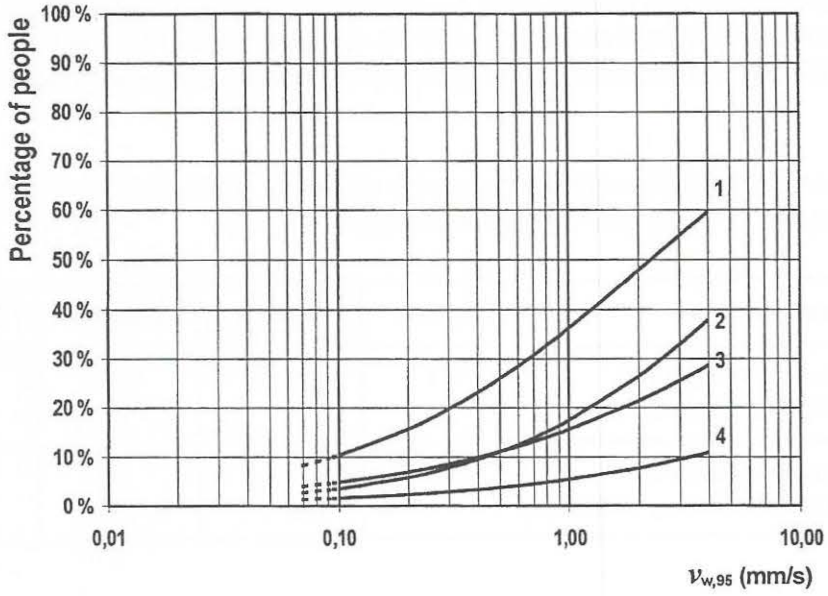
1	Perceives vibrations
2	Highly, moderately and slightly annoyed of vibrations
3	Highly and moderately annoyed of vibrations
4	Highly annoyed of vibrations

Figure 1: The percentage of persons with various degrees of annoyance due to vibrations in dwellings, plotted against calculated statistical maximum values for weighted velocity, $v_{w,95}$ *in mm/s*

Exposure-effect curves for disturbance of rest and daily activities

In the sociological survey, studies of various other effects of vibrations and influence on daily activities in the dwelling were included. Effects like that the building vibrates, things rattle or shake, things are displaced, or the person feels the vibrations with the body were surveyed. The exposure-effect curves in figure 2 show the population's response to vibrations that cause these various effects in the dwelling.

Vibrations from transport are mainly perceived in that the house vibrates. There are fewer people who 'frequently notice that things are displaced'. Even at high vibration values, only 10 % of the persons responding to the survey, indicate that this happens often. At a statistical maximum value for weighted velocity, $v_{w,95}$, of 0,4 mm/s, about 10 % of the respondents report that they "often feel vibrations with the body". Those who are highly annoyed, report more frequently that vibrations often occur.



Key

1 The building often vibrates
2 Feeling often vibrations with the body
3 Furniture and fixtures often rattle
4 Things are often displaced

Figure 2: Percentage of persons perceiving vibrations in various ways, plotted against the calculated statistical maximum value for weighted velocity, $v_{w,95}$, *in mm/s*

Vibration classification of dwellings

A vibration classification system similar to the one made for the acoustic conditions in NS 8175[9,17], was prepared by using limit values in terms of the statistical maximum velocity or acceleration ($v_{w,95}$ or $a_{w,95}$). Four classes (A, B, C and D) were defined by grouping the people's perception found in the Norwegian study[4,5,6] and by assessments based on experience from such measurements. In the choice of classes and limits, consideration has been given to the existing sound classification for buildings. The intention was to make a comparable classification, but the knowledge of vibration effects on human beings is much more limited than the corresponding knowledge on acoustics. The specified limits are therefore for guidance and may require additional assessments (cf. next sections).

The value 0,1 mm/s has been chosen as the limit for the class A corresponding to very good vibration conditions where people are expected to be disturbed only as an exception (see next section). So, the inhabitants in class A dwelling will normally not be expected to notice vibrations. In dwellings of class B, relatively good vibration conditions are achieved, although inhabitants may be expected to be disturbed by vibrations to some extent.

Class C gives the minimum vibration requirement for new residential buildings and in connection with the planning of new transport lines and constructions. The limit value 0,3 mm/s was chosen as a recommended value for the new buildings corresponding to about 8 % highly *annoyed* people, as mentioned earlier. About 15 % of the exposed persons in these dwellings may be highly or moderately *disturbed* by vibrations.

Limits in class D are to be achieved for existing dwellings when the cost-benefit considerations make it unreasonable to require class C. Almost 25 % of persons may then be highly or moderately *disturbed* by vibrations. Thus, serious attempts should be made to meet Class C requirements. This was chosen as the class limit for old building in order to take measures.

Table – Guidance classification of dwellings with the upper limits for the statistical maximum value for weighted velocity $v_{w,95}$ *or acceleration* $a_{w,95}$

Type of vibration value	**Class A**	**Class B**	**Class C**	**Class D**
Statistical maximum value for weighted velocity, $v_{w,95}$ (mm/s)	0,1	0,15	0,3	0,6
Statistical maximum value for weighted acceleration, $a_{w,95}$ (mm/s^2)	3,6	5,4	11	21

Although the percentages of annoyed may seem to be quite high, the limits are in general more stringent than in the recommendations given in the previous studies by Brekke and Madshus[2]. The limit of 0,4 mm/s has been practised for new buildings and 1,0 mm/s for condemnation of old buildings. Various measures have been taken in the vibration area between these limits, depending on the cost-benefit considerations.

Assessment of vibrations in regulations in relation to the human perception

In the selection of vibration classes there are several factors that ought to be taken into account. An evaluation of possible vibration problems should especially be made, if the ground consists of soft soil layers (e.g. clay, marshland, soil with a high content of organic material, silt), and there are sources of vibration near a planned residential dwelling, or new transport lane lines are planned causing vibrations at either existing or planned residential buildings.

The purpose for and use of the building is essential. Alternative land-use plans and building solutions ought to be made in order to prevent vibration nuisance, when there is a possibility of vibrations occurring, and problems may be foreseen. It is both more difficult and more expensive to take measures to reduce vibrations in the future than to reduce noise, for example. If both noise and vibrations occur, it should be evaluated whether to choose a class with lower (stricter) limits than if vibrations occur alone. The combined effects of noise and vibrations may cause greater nuisance for residents than those assumed in connection with the different classes (cf. next section).

The vibration measures that are used in the classification do not take into consideration all aspects of the vibration sources (frequency and duration of vehicle passings, total traffic volume, etc.), and so there is a certain amount of uncertainty related to the measures. Evaluations of the cost-benefit ratio in the connection with measures are therefore important. Also, the dose-effect curves show the average effect and hence it cannot be deduced from the curves that certain groups can be more sensitive to vibrations, or exposed to several environmental stresses.

Combined effects of noise and vibrations – Total annoyance

In evaluating responses to vibrations in buildings, noise is an important parameter, which, in addition to the vibrations, will affect the total annoyance, and both conditions should always be taken into consideration. In many cases, one finds in connection with vibrations in buildings that low frequency noise occurs at the same time, and that the furniture, windows and pictures are shaking. The sum of these combined effects of noise and vibrations will probably amount to the total perceived nuisance for the residents. If reactions are evaluated solely on the basis of measured vibrations, the total perceived nuisance may be underestimated. So far, no simple method has been found for the measurement or evaluation of the total perceived nuisance when combined effects are included. A number of laboratory experiments and sociological field experiments have been conducted on the combined effects of noise and vibrations. The results of these experiments differ somewhat from one another, but some main conclusions can be drawn and have been summed up in the following.

In places with moderate or low vibration values (corresponding to class C or better), and high indoor noise levels, noise will be the dominant nuisance for the residents. In places with powerful vibrations (higher values than in class C), the vibrations can frequently be the dominant nuisance. The total nuisance will be considerably higher in such cases than the corresponding total nuisance in places with the same noise level but low vibrations. If, for example, a building is protected by a noise barrier or its facade is insulated so as to give low indoor noise levels, no particular reduction in nuisance may be expected in locations where there are powerful vibrations. Considerations of the existing literature seem to show, that noise will dominate the perceived nuisance if the vibrations are moderate, and the noise is loud. On the other hand, vibrations will dominate the perceived nuisance if the vibrations are powerful, and the noise is moderate. For other combinations of vibrations and noise, it seems to be more uncertain whether the noise or vibrations are the most dominant source for the nuisance or disturbance perception. It has, however, been demonstrated that vibrations are perceived to be more disturbing when they occur simultaneously with noise.

Conclusions

The standard is based on experimental data from Norway and qualified experience from vibration measurements and problems of several Norwegian experts in this area. The standard will be an object to continuos evaluation and the limits are also given as guidance. In a longer perspective, the quality of the buildings with respect to vibration conditions is generally expected to be improved. This new concept is expected to bring about awareness about the possibilities of improving and making more adequate building construction works which again may improve the quality of living.

The vibration problems are expected to be reduced or avoided to a greater extent, but more research both on an international and national level is strongly desirable. One may expect, at least to a certain degree, that the conditions are similar in other countries, too. The statistical maximum value does not include direct considerations of the frequency of the vibrations events and may cause some uncertainty of the vibration dose. Also, experience from vibration measurement data combined to human effects should continuously be gathered and used in future revisions of this standard. Human perception of vibrations and relation to other environmental factors is needed in order to improve the understanding of combined effects and to make adequate efforts to reduce the total nuisance from transport sources.

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Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
Henrik Møller & Morten Lydolf

The Evaluations of Horizontal Whole-Body Vibration in the Low Frequency Range

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Summary

There were presented in International Standard 2631 for a resident on the reaction of horizontal vibration from a building, a public traffic system, and the structure of ocean and so on. These effects were not evaluated yet by physiological method for the present. In the preceding, it showed that the criterion curve evaluated a psychological method on the comfortable and uncomfortable feelings and did not establish by using the physiological data up to now.

Physiological and psychological effects of low frequency horizontal vibration on the whole-body were as follows: Change in the autonomic nervous system were observed, and the system tended to change from the state of predominance of the parasympathetic nervous system to that of the sympathetic nervous system when frequency exceeded the range 0.2 to 0.4 Hz, including round 0.3 Hz.

Introduction

In this study, it tested the difference between triangular wave and sinusoidal wave to find the physiological and psychological effect, and for exposure below 0.1Hz, the psycho-physiological effects have objectively shown.

The study has adopted a physiological measuring method of reflex of the autonomic nervous system and has adopted a psychological measuring method of evaluation of the introspective five and seven grades according to the twenty items.

By proposing, psycho-physiological effects examined based on the exposure of the low frequency and using the said data, the exemplification of the measurement is given.

Furthermore the figures in these new data on physiological effects have made it possible to exhibit the applicability to the standard for the evaluation of a lower range.

Method

The study was performed using multi-input vibration testing equipment in the large structure testing building at this faculty. This vibrator was a piece of experimental equipment able to vibrate at exact frequencies ranging from 0.01 to 50Hz with maximum amplitude of 200mm, by computer control. A legless-chair was mounted on the vibration table, and a subject was exposed to the vibrations, and sat with his legs down. The amplitudes of vibration table were 15, 25, 50, 100, 125, 150, 175 and 200mm: frequencies ranged from 0.01Hz or more; Rms values of vibratory acceleration ranged from approximately 0.000042 m/s^2 or more. Exposure time was a 15-minute, and the frequency amplitude of vibration was changed randomly. Physiological effects were examined by investigating the effects on the cardiovascular system, respiratory movement and salivation, to confirm the effects on the autonomic nervous system (sympathetic and parasympathetic nervous systems). Measurement was performed for 30-second at 3-minute intervals after starting vibration in the cases of heart rate and respiratory rate. In the case of saliva secretion, the dental cotton roll was replaced at 3-minute intervals to measure the secreted quantity over 3-minute. Figure 1 shows a time table used when measuring whole-body vibration in exposure with a measuring method.

Results and Conclusions

Effects on the autonomic nervous system appeared as changes in heart ratio, respiratory rate and quantity of saliva secretion. The heart-rate ratios and respiratory ratios tended to decrease in the case of vibration with frequencies of less than 0.08Hz, but increase in the case of frequencies of more 0.2Hz. The ratio of saliva secretion tended to increase in the case of vibration with a frequency of 0.01, 0.015, 0.02, 0.03Hz. The autonomic nervous system tended the state of predominance of the parasympathetic nervous system. Respiratory-rate ratios tended to decrease in the case of vibration with frequencies of less than 0.2Hz, but increase in the case of frequencies of more than 0.2Hz, when amplitudes were 125 and 175mm. The ratio of saliva secretion tended to increase in the case of vibration with frequency of 0.1Hz and amplitude of 125 or 175mm, and it tended to be close to the reference value, or decrease, in the case of vibrations with other frequencies. On the subjects, the small ratios at 125mm-0.56 m/s^2, 175mm-0.78 m/s^2, showed a restraint tendency. By using this data, other method of physiological evaluations of the whole-body vibration have been developed. The calculation values (X_{p}, Y) can also be compared with the physiological indication shown in Table 1, 2, and Figure 2. The absolute value for the state of autonomic nervous system of whole-body vibration in the low frequency range below 1 Hz is, a magnitude of Y are considered effective.

Psychological evaluation by the introspective method of numerical values showed that five and seven grades were converted to scale numbered (1-5, 7) in which "3", "4" represented "normal". It was believed that when the acceleration was "unpleasant" to exceed 0.20 m/s^2 and that low frequency area which gave "quite pleasant" for 0.000070-0.05 m/s^2. Those of data were shown at frequency range from 0.01 to 0.1Hz.

This study revealed that subjects received physiological influences when rms values of vibratory acceleration reached 0.56 m/s^2.

In the sinusoidal wave, as rms values of vibratory acceleration increased, sensation of vibration tended to change from " pleasant " to " unpleasant ". On the subjects, 0.67 m/s^2 or 0.78 m/s^2 decreased to 2.6, 2.8 of the evaluation value.

The feeling parts for evaluations shown in Table 3 should be considered to be representative of their physiological effects.

In the triangular wave, these data were obtained for the effects of physiological measuring method. The heart-rate ratios were more than one in the case of vibration with amplitudes of 25, 50, 100,125, 150mm and frequencies of 0.2, 0.3, 0.6Hz, and acceleration 0.11, 0.13, 0.14, 0.17, 0.25 m/s^2. Respiratory-rate ratios tended to increase in the case of frequencies of more than 0.1Hz, so that 0.2, 0.4, 0.6Hz, amplitudes were 25, 50, 100, 125, 175mm, acceleration at 0.05, 0.11, 0.14, 0.22, 0.25 m/s^2. The ratio of saliva secretion tended to decrease in the case of vibration with amplitudes of 25, 50, 100, 125, 150, 175mm; besides there were for the center of 0.3Hz from 0.2Hz and there were an experimental points at an acceleration of 0.13, 0.14, 0.22, 0.25 m/s^2. Ratios of movement-area tended to increase with amplitudes of 25mm, 50mm, 100mm, 125mm, 150mm, 175mm, frequency of 0.2, 0.6Hz, and acceleration at 0.11, 0.14, 0.17, 0.25 m/s^2. For the reasons mentioned above, the autonomic nervous system was observed that it was the state of the sympathetic nervous system. With the vibration of the acceleration till 0.063 m/s^2 were " quite pleasant ", resulting in the fact that the difference between the acceleration of 0.25 m/s^2 and less than 0.063 m/s^2.

The T-test was appearance at 0.31 m/s^2. ($p<0.1$, level:1-5, $p<0.05$, level:1-7)

The same adjectives of physiological tendency were "hard", "great", "strong", "violent", "sharp", "aggressive" and "speedy". The difference in evaluation at point, at which the wave was not the same, showed contribution on the effects of acceleration.

Since evaluation of the measurement method of such factors enables use to comprehend the psycho-physiological effects to make introduction to applied the standard, usefulness to the designed traffic system and the comfort system have been successfully exhibited.

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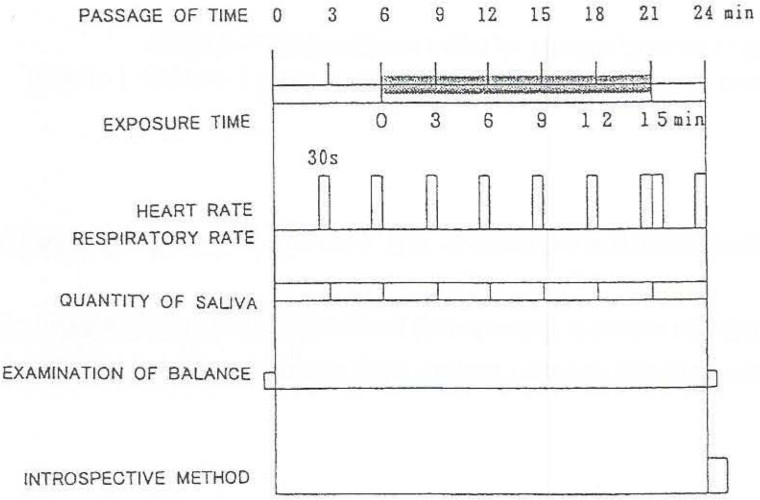

Figure 1: Time table for physiological and psychological method.

Table 1: Thereby the following set of equation was used.

Example: 150mm, 0.2Hz, 0.17m/s² (A quantity of saliva secretion ratio)

The equation becomes

$$Y_p = y_p - x_p y_n / x_n \qquad (1)$$

X_p: value of accumulation for 15-minute, y_n: each time, X_n: every 15-minute,

y_p: value of accumulation every each time Y_p is function of a parameter X_p

The value of fluctuation Y can be calculated using the equation.

min	ratio		y_p	Y_p
3	0.682	-0.318	-0.318	$Y_3 = -0.318 - 3 \times (-0.827)/15 = -0.1526$
6	0.774	-0.226	-0.544	$Y_6 = -0.544 - 6 \times (-0.827)/15 = -0.2132$
9	0.925	-0.075	-0.619	$Y_9 = -0.619 - 9 \times (-0.827)/15 = -0.1228$
12	0.884	-0.116	-0.735	$Y_{12} = -0.735 - 12 \times (-0.827)/15 = -0.0734$
15	0.908	-0.092	-0.827	$Y_{15} = -0.827 - 15 \times (-0.827)/15 = 0$

A cumulative value of quantity of saliva secretion ratio= -0.827:X_p

A fluctuation value of quantity of saliva secretion ratio= $| -0.2132 | = 0.21$:Y

Example: 150mm, 0.015Hz, 0.00094m/s² (A quantity of saliva secretion ratio)

min	ratio		y_p	Y_p
3	1.249	+0.249	+0.249	$Y_3 = 0.249 - 3 \times (0.767)/15 = 0.0956$
6	1.447	+0.447	+0.696	$Y_6 = 0.696 - 6 \times (0.767)/15 = 0.3892$
9	1.226	+0.226	+0.922	$Y_9 = 0.922 - 9 \times (0.767)/15 = 0.4618$
12	0.929	-0.071	+0.851	$Y_{12} = 0.851 - 12 \times (0.767)/15 = 0.2374$
15	0.916	-0.084	+0.767	$Y_{15} = 0.767 - 15 \times (0.767)/15 = 0$

A cumulative value of quantity of saliva secretion ratio= +0.767:X_p

A fluctuation value of quantity of saliva secretion ratio= $| +0.4618 | = 0.46$:Y

The results of these calculations are depicted in Fig. 2 for the following two type (Autonomic nervous system:

a) the state of the sympathetic nervous system with evaluation of the physiological effects.

b) the state of the parasympathetic nervous system with evaluation the physiological effects.

Table 2: The calcuations of X_p and Y for the Heart-rate ratio and the Respiratory-rate ratio.

	male :lateral (y-axis)	X_p	Y
Heart-rate ratio	150mm,0.04Hz,0.0067m/s^2	0	0.02
	125mm, 0.3Hz, 0.31m/s^2	+0.27	0.03
Respiratory-rate ratio	50mm,0.04Hz,0.0067m/s^2	-0.10	0.10
	125mm, 0.4Hz, 0.56m/s^2	+0.60	0.13
	female:fore and aft (x-axis)		
	50mm, 0.4Hz, 0.22m/s^2	+0.11	0.10

There can be the differences between subjects. X_p was a minus value or 0 below 0.04Hz with y-axis vibration and was a plus value more 0.3, 0.4Hz with X, y-axis vibration. The state of the autonomic nervous system analyzed by using a minus and plus value.

These values are effective measures against the physiological indication.

Table 3: Feeling parts of the sinusoidal wave (lateral:y-axis) by Introspective method.

male : n=8	Feeling parts
100mm, 0.04Hz, 0.0045m/s^2	abdomen40%, upper arm40%, ankle 20%
15mm,0.01Hz, 0.000042m/s^2	head34%, abdomen33%, ankle33%
25mm, 0.8Hz, 0.45m/s^2	head27%, upper arm22%, ankle17%, neck-shoulders11%, chest11%
125mm, 0.4Hz, 0.56m/s^2	abdomen12%, upper arm16%, ankle16%, head16%, chest16%, neck-shoulders12%
150mm, 0.4Hz, 0.67m/s^2	abdomen19%, upper arm17%, ankle15%, neck-shoulders15%, head12%, back12%

The number of the feeling parts has increased that the acceleration is greater than 0.45m/s^2.

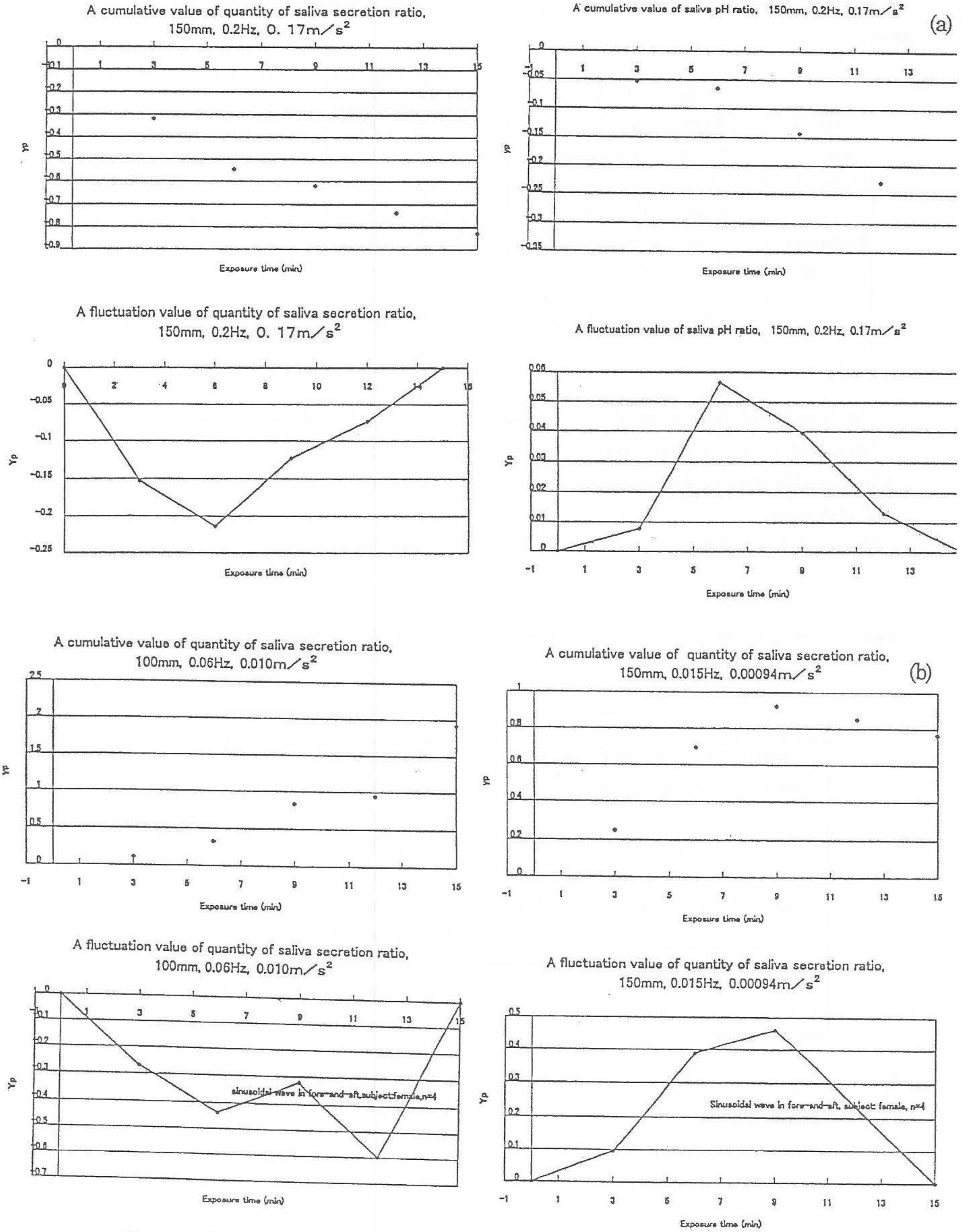

Figure 2: A cumulative value and a fluctuation value of the calculation for saliva.

Aalborg 2000
Low Frequency
Noise
and Vibration

9th International Meeting
17th-19th May, 2000
Aalborg, Denmark
Proceedings edited by
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Study on perception of complex low frequency sounds

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Summary

Hearing thresholds of complex low frequency sound and masking by low frequency sound were measured. The hearing threshold levels of complex sounds were lower than the thresholds of pure tones, which have the same frequency as the fundamental, even if the levels of all harmonic components are under the threshold levels. The masking values were almost negative when the measuring frequency is below 20Hz. It is supposed that the fundamental and the over tones are not heard separately but are heard as one kind sound. The harmonic components or the over tones affect to strengthen the fundamental wave.

Introduction

Not only pure tones, there are many complex low frequency sounds generated from various sources. The complex sound that consists of several pure tones can be separately heard, if the number of the component is not many, and if the component frequencies do not close very much. Masking effect is deeply connected with hearing of complex sound. Hearing thresholds of complex low frequency sound and masking valued by low frequency sound were measured. The mutual effect of the fundamental and the over tones were investigated at low frequency area.

Measurement of hearing thresholds of pure tone and complex sound

Hearing thresholds were measured in the chamber with the size almost equal to a phone booth. Four loudspeakers whose diameter is 40cm are installed. As this booth is being put in the sound measurement room, the background noise is enough small. Hearing thresholds of pure tones were measured. The frequencies of the test tone are 5, 10, 20, and 40Hz. Five students whose hearing is within the normal range participated in the experiment as a subject. Psychometric method is a method of limits. Figure 1 shows experimental set up.

Hearing thresholds of complex sound were also measured in the same way. Sound signals of complex sound were synthesized by computer. The fundamental frequencies are 5, 10 and 20Hz. They have several harmonics. The level differences between fundamentals and harmonics are equal to the level differences of the thresholds for pure tones. The level differences of these components do not change during the experiment. The results of hearing threshold of pure tone and complex sound are shown in Figure 2. The values are the average of 5 subjects. The hearing threshold of pure tone and complex sound of one subject are shown in Figure 3. The hearing threshold of complex sound is indicated in each component.

With this result, the hearing threshold levels of complex sound were lower than the threshold levels of pure tones, which has the same frequency as fundamental sound, even if the levels of all harmonic components are under the threshold levels of the same frequency pure tone. It is said that the human ear is able to analyze a periodic sound wave into its sinusoidal components. This does not agree with this result. Therefore, it is considered that the complex sound is not able to be heard separately to each component at low frequency area.

Hearing threshold of complex sound with various levels of harmonic

Hearing thresholds of the complex sound with various levels of harmonic were measured. The complex sound that has the fundamental of 5Hz with the second harmonic of 10Hz was used. The measuring method is equal to the method used in above. New three subjects were participated in the experiment. Their hearing is within the normal range. The average of hearing thresholds of three subjects is shown in Figure 4. The negative value means that the

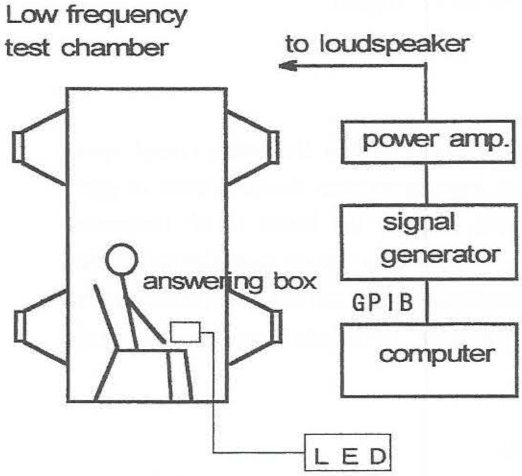

Figure 1: Measuring set up.

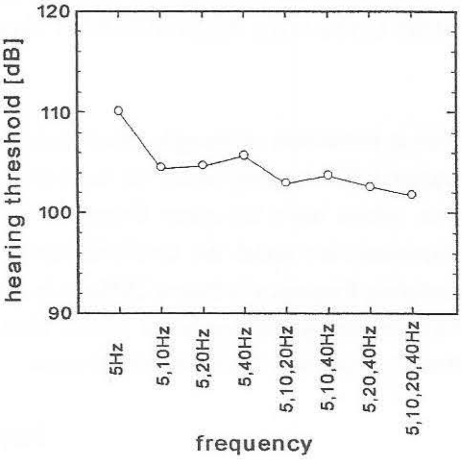

Figure 2: Hearing threshold of complex sound.

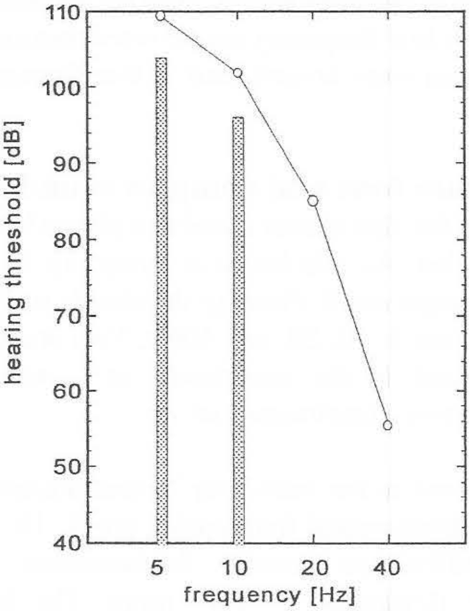

Figure 3: The component levels of hearing threshold of complex sound. The unfilled circles represent the thresholds of pure tones.

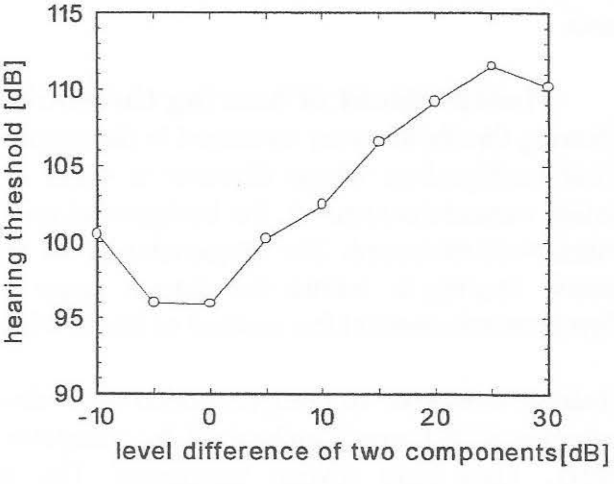

Figure 4: The hearing threshold of complex sound that has various level differences of two components. The fundamental is 5Hz and the second harmonic is 10Hz.

level of fundamental is smaller than that of harmonic.

In the result, the hearing threshold of the complex sound is the smallest when the level differences are -5dB and 0dB. The threshold is 96dB. This value is smaller than the hearing threshold of 10Hz pure tone. The hearing threshold gradually increases, as the level difference increases. The hearing threshold reaches 112dB, when the level difference is 25dB, and this value is almost equal to hearing threshold of 5Hz pure tone. The hearing threshold does not increase over 25dB of the level difference. The hearing threshold approaches the threshold of 10Hz pure tone at 100.5dB, when level difference is -10dB.

Hearing threshold of complex sound which have various phase differences of fundamental and harmonic

The result of the previous chapter explains that the hearing of complex sound is affected by the harmonics even if the harmonics are not audible. It is considered that the hearing of low frequency sound depend on the waveform. The hearing thresholds were measured using the complex signals that have various phase differences between the fundamental and the harmonic. The example of the waveform is shown in Figure 5.

The waveform of complex sound is given as follow.

$$a = a_1 \sin(2\pi f t) + a_2 \sin(2\pi n f t - \phi) \qquad (1)$$

f : frequency n=2,4,8

ϕ = 0,30,60,90,120,180,240,300 degree

The level difference of a_1 and a_2 is the same as that of the hearing thresholds of two frequencies. The fundamental frequencies are 5,10 and 20Hz. Two subjects are participated. The measuring method is equal to the method used in the previous chapter.

One of the results is shown in Figure 6. The hearing thresholds are periodically changed as the phase difference increases. The hearing thresholds are smaller when the phase differences are 90 and 300 degree, and bigger when the phase difference is 180 degree. To explain the threshold change, the relative peak levels of the synthesis wave were calculated and shown in Figure 6 with filled circles. The relative peak levels are also periodically changed. The

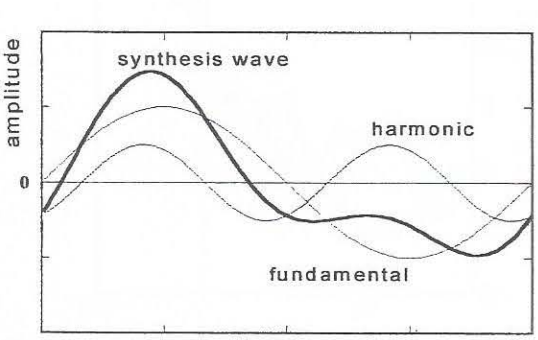

Figure 5:The waveform of complex sound that have the phase difference between the fundamental and the harmonic.

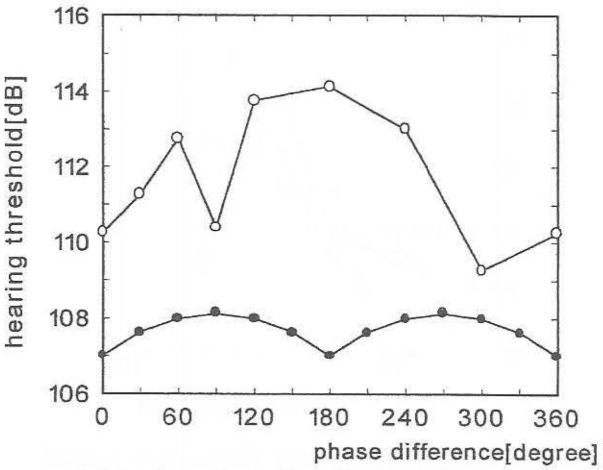

Figure 6:The hearing thresholds of complex sound that have various phase differences between the fundamental and the second harmonic. The fundamental is 5Hz. The filled circles represent the relative peak levels.

hearing threshold is big when the relative peak level is small. The reason is explained like this. It is expected that the fundamental tone and the harmonic tone are not separately audible, but the complex sound is audible as one sound. The sound pressure level was not changed in the chamber while the phase difference was changed. Therefore, the bigger sound pressure is needed to hear the complex sound when the relative peak level is small. It seems to be the reason that the hearing threshold of complex sound is changed as the phase difference is changed.

Masking effect of low frequency sound

Hearing of complex sound and masking effect have closely been connected. The measurement of masking by low frequency sounds was carried out. The masker is pure low frequency sound whose frequencies are 5,10,20 and 40Hz. Two subjects were participated. Hearing thresholds were measured under the low frequency sounds. Hearing thresholds also measured without the low frequency sounds. The level differences between them are masking values. The measurement frequencies are every one-third octave steps at the frequencies from 5Hz to 50Hz. The result is shown in Figure 7 and 8. The masking value increases as the masker level increases. The masking value becomes smaller as the frequency of the masker becomes lower and the masker level becomes smaller. The masking values are almost negative when the measuring frequencies are below 20Hz. This means that the masker does not disturb to hear these sounds but affect to strengthen the maskee and make be easier to hear the sound.

Conclusion

From the above fact, it is possible to sum up like the following. The complex low frequency sounds are perceived even if the component levels are smaller than the hearing thresholds of pure tone. The masking values by low frequency sound are negative at the frequencies lower than 20Hz under the small masker level. The low frequency sound becomes easier to be audible due to the masker. It is supposed that the fundamental and the harmonic components or the over tones are not heard separately but are heard as one sound and the harmonic components or the over tones affect to strengthen the fundamental wave.

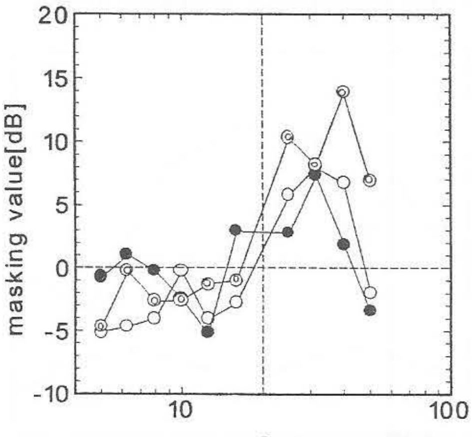

Figure.7: Masking by low frequency sound. The masker is 20Hz pure tone whose levels are 87 (○) ,90 (●) and 95dB (◎) . They are 1.2dB, 4.2dB 9.2dB greater than the hearing threshold.

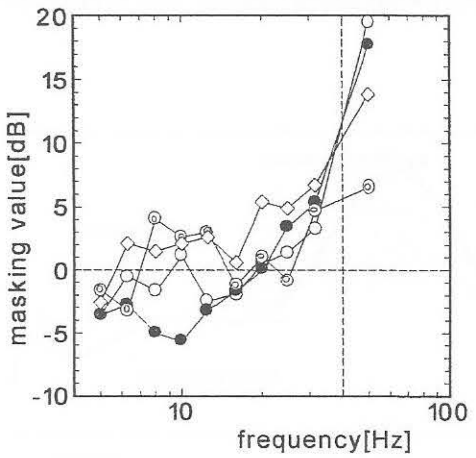

Figure.8: Masking by low frequency sound. The masker is 40Hz pure tone whose levels are 63 (○) ,68 (●) and 73 (◎) and 78dB (◇) . They are 1.3,6.3,11.3 and 16.3dB greater than the hearing threshold.

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Does low frequency noise induce stress?

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Summary

To study the possible interference of low frequency noise on stress experienced during performance, test persons classified as sensitive or non-sensitive to noise in general or to low frequency noise, worked with different performance tests in a noise environment with dominant low frequencies or dominant middle frequencies, both at a level of 40 dB LAeq. The effects were evaluated as changes in cortisol in saliva, taken at different times before and during the test. The results showed that normal circardian downward drift of cortisol was not significantly modulated by either noise condition or subject-sensitivity to noise, alone. It was however modulated by a combination of both, such that the decline in cortisol was significantly less for subjects who were both sensitive to noise *and* exposed to low frequency noise.

The results also point towards a correlation between base-corrected cortisol during the experimental period and base-corrected stress reporting during the low-frequency noise condition.

1. Background

There is a growing body of data showing that low frequency noise has effect characteristics that are different from other environmental noises at comparable levels [Persson Waye 1995, Berglund *et al* 1994]. The exposure to low frequency noise during work and recreation has been found to cause general annoyance [Persson Waye and Rylander 2000, Persson Waye et al 1997] as well as impaired response time in performance tests among persons sensitive to low frequency noise [Persson Waye et al 1997]. In occupational environments, low frequency noise often origins from large ventilation- or air conditioning systems but may also be the result of attempts to attenuate loud noise as attenuated noise contain a larger proportion of low frequencies. The new working conditions for personnel in control rooms and offices has led to a change of demands, involving a high element of unpredictability, selective attention, processing of a high load of information and the work is to a great extent paced by computers. The knowledge on how such work demands are effected by the extra loading of LFN exposure is scarce, but it is plausible that the noise load would put an extra strain on the individual that could be interpreted as stress.

The results from performance tests in a recently completed study demonstrated that low frequency noise interfered with a proof reading test by decreasing the number of markings made per line read, and in a grammatical reasoning test the response time became longer over time in the low frequency exposure [Persson Waye *et al* in preparation]. The results further showed that the subjects reported a higher degree of annoyance and work impairment when working in low frequency noise, and that subjects classified as sensitive to low frequency noise or to noise in general may be at highest risk.

The present study was undertaken to investigate if the stress experienced during working with performance tests resulted in an increased secretion cortisol levels in saliva. Elevations in cortisol concentration reflect together with cardiovascular and other neuroendocrine measures various aspects of the stressfulness of the individual´s interaction with the environment Lundberg et al [1993]. According to the model of Frankenhaeuser [1989] the pituitary-adrenal cortical activation, with the secretion of cortisol, is associated with "negative stress" (feelings of distress, anxiety, helplessness and depression).

Part of the experiment describing the effects on performance test has been reported previously [Persson Waye *et al* in preparation]. The study comprised subjects who performed four performance tests during exposure to a low frequency noise or a reference noise at the same sound level.

2. Material and methods

2.1 General structure. Female and male subjects worked with a series of performance tests and were continuously exposed to low frequency noise or a reference noise. To assess test induced stress and to evaluate the difference in stress between the two noises, saliva samples were taken and the amounts of cortisol were determined. In addition, the subjective stress during the test session was evaluated using questionnaires, asking for experienced performance, annoyance and stress. The subjects were classified as sensitive or not sensitive to noise in general or to low frequency noise using a questionnaire.

2.2 Noise exposure. Two types of noise were used. The first noise (reference noise) was recorded from a ventilation installation and had a mid-frequency spectrum. For the second noise (low frequency noise) sound pressure levels in the frequency region of 31.5 to 125 Hz were added to the ventilation noise using a digitalised sound processor system (Aladdin interactive workbench, Nyvalla DSP Stockholm, Sweden). Furthermore, a tone at 31.5 Hz was amplitude-modulated with an amplitude frequency of 2 Hz (Figure 1). Both noises had a level of 40 dBA. The experiment was performed in a 24 m^2 room, furnished as an office with desk, computer and bookshelf as described previously [Persson Waye *et al* in preparation].

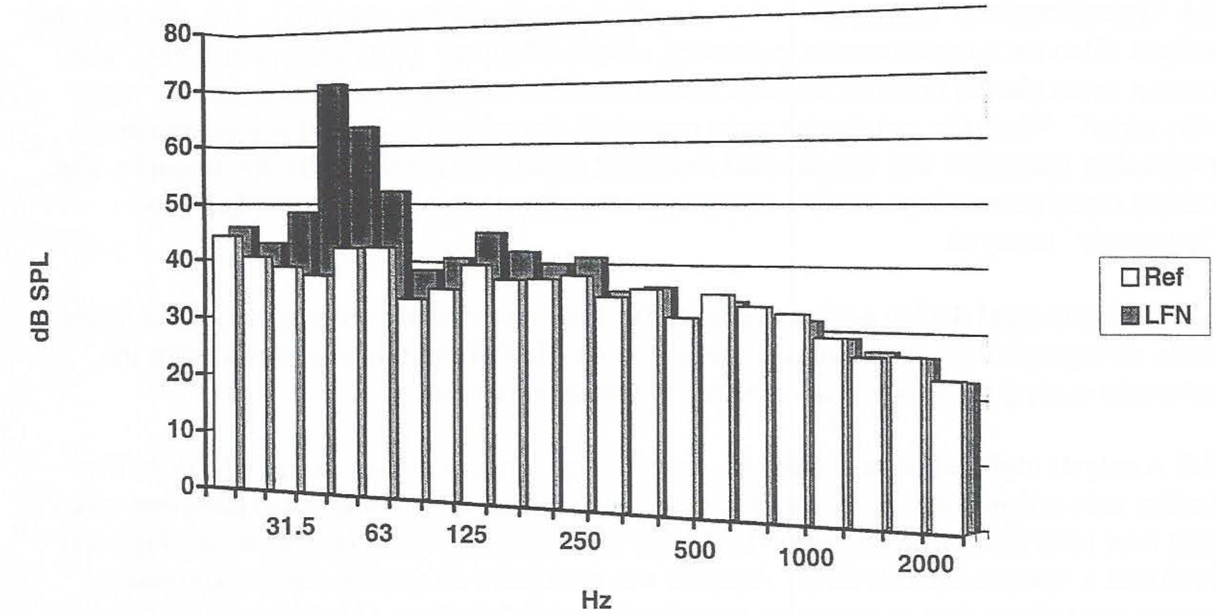

Figure 1. Third octave band sound pressure levels of reference (light coloured bars) and low frequency noise used during the performance tests.

2.3 Subjects. In the study 19 female and 13 male subjects with an average age of 24.3 years took part. Each person underwent a hearing test (with a SA 201 II Audiometer, Entomed, Sweden) and only persons with normal hearing, <20 dB HL, were admitted to the test. Sensitivity to noise in general and sensitivity to low frequency noise was determined using questionnaires as previously reported [Persson Waye *et al* in preparation].

2.4 Performance tests. In the experiment four performance tests were used. Initially, two simple reaction time tests were used, followed by a proof reading task and a verbal grammatical task demanding higher cognitive attention. The tests have been described in detail previously [Persson Waye *et al* in preparation]. The experiment consisted of two sessions, 2.5-3 hours each, on separate days and always in the afternoon. During each test session, the subjects worked with the four performance tests twice (phase A and B) and were instructed to work with the tests as correct and fast as possible. During the experiment they were exposed to the reference or to the low frequency noise.

2.5 Determination of cortisol. Saliva samples were taken by asking the test persons to chew on a cotton salivette (Sarstedt Ltd, UK) for 3 minutes, after which it was frozen at - 70°C until analysed. To allow for a proper baseline level, the subjects came to the laboratory and relaxed for 20 minutes before the first sample was taken. During the phase A of the session four samples were taken with approximately 10 minutes intervals. A final sample (post base) was taken at the end of the second session (after 160 min). In total six samples were taken, of which the first sample will serve as a base linevalue, the second to the fifth sample will reflect stress during the different tasks and the sixth sample will serve as a post base at the end of the test session.

Suspensions were prepared from the saliva and cortisol were determined by a method previously described [Glover *et al* 1980, Doyle *et al* 1996].

2.6 Questionnaires. During the test session and after the saliva samples 1, 2, 3, 4 and 6, the subject filled out a questionnaire evaluating stress and energy [Kjellberg *et al* 1989]. The subject could choose between six response alternatives ranging from "not at all" to "very, very much". When the test session was completed, the subject answered a questionnaire evaluating annoyance due to noise and perceived impairment of the tasks due to noise. The subject could choose between five response alternatives ranging from "not at all" to "extremely" annoyed.

2.7 Experimental design and procedure. The test consisted of two sessions, 2.5-3 hours each, on separate days and always in the afternoon. Half of the subjects started with the reference noise and the other half with the low frequency noise.

2.8 Analysis and statistical methods. Analysis was carried out by a 3x2x2 ANOVA. Two factors were within-subjects: Period (pre-base, mean of measures during the experiment, and post base) and Noise Condition (low frequency and reference). Sensitivity to Noise (high and low) was a between-subjects factor. Analysis was performed on cortisol values expressed as square-roots of raw data to counteract initially skewed distributions. Correction did not change any significance decision and original degrees of freedom are reported along with attendant p values. Within-subjects effects were routinely checked for continued significance following Greenhouse-Geisser correction for sphericity when appropriate. Although omnibus effects are reported if significant, primary tests of hypotheses were carried out using orthogonal comparisons of the experimental period compared to the mean of both base values, and then a comparison of both individual base values.

In view of the known circadian downward drift of cortisol during the day (see below), there is a need to compare observed cortisol values during the experimental period with an average of before and after values. In effect, this average amounts to an interpolated control estimate under the null hypothesis for what cortisol values might be expected to be in the absence of experimental manipulation. In the analysis of the relationship between cortisol levels and subjective stress rating, the values were analysed in relations to their initial values (base values).The statistical analyses were done using SPSS [SPSS base 7.5 for Windows]. All tests were two-sided and a p-value of <0.05 was considered as statistically significant.

3. Results

3.1 Cortisol Analysis. A first analysis were done to see whether cortisol levels during the experimental period as a whole (relative to before and after base readings) differed by noise condition and/or prior reported sensitivity of the subject to general noise.

There was a highly significant main effect of Period (F=16.43; df=2,56; p<.001). Means for all subjects, aggregated over the two noise conditions, are shown in Figure 2.

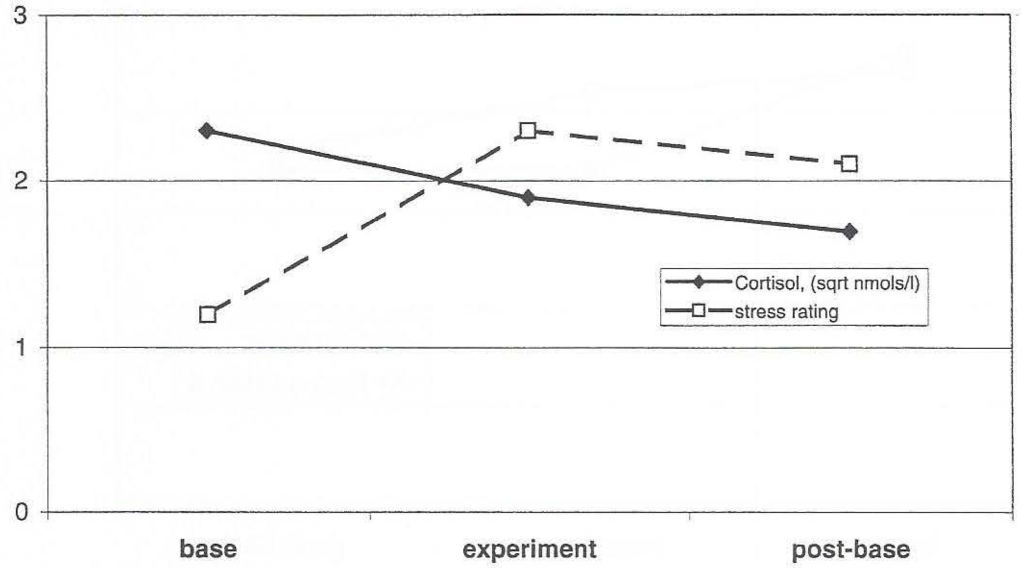

Figure 2. Mean cortisol and stress ratings for all subjects averaged over noise conditions for base, experimental period, and post base.

In accordance with expectation based on known circadian effects, cortisol was significantly decreased at the last sampling point compared to the first (base) point (t=4.70; p<.001). The overall mean for experimental period data was intermediate between pre and post base and not significantly different from either, indicating gradual downward drift of cortisol over the trial as a whole. There were no significant interactive effects of either noise nor sensitivity factors in relation to the cortisol pattern over time. In particular, cortisol levels (compared to the average of base and final values) were not significantly higher in the low frequency condition, nor among noise-sensitive subjects. However a significant 3-way interaction between noise condition, sensitivity of subject, and period was obtained for this key comparison (t=2.49; p<.019).

Consequent analysis of simple effects indicated that in the low frequency noise condition, noise-sensitive subjects maintained higher cortisol levels, relative to base values, during the experimental period than non-sensitive subjects (t=2.03; p<.05). In the reference noise condition, there was no difference between sensitive and non-sensitive subjects. Thus higher relative cortisol values during the experiment are associated with the combination of being noise sensitive and being in a low frequency noise condition. The means for sensitive and non-sensitive subjects in the low frequency noise condition are plotted in Figure 3.

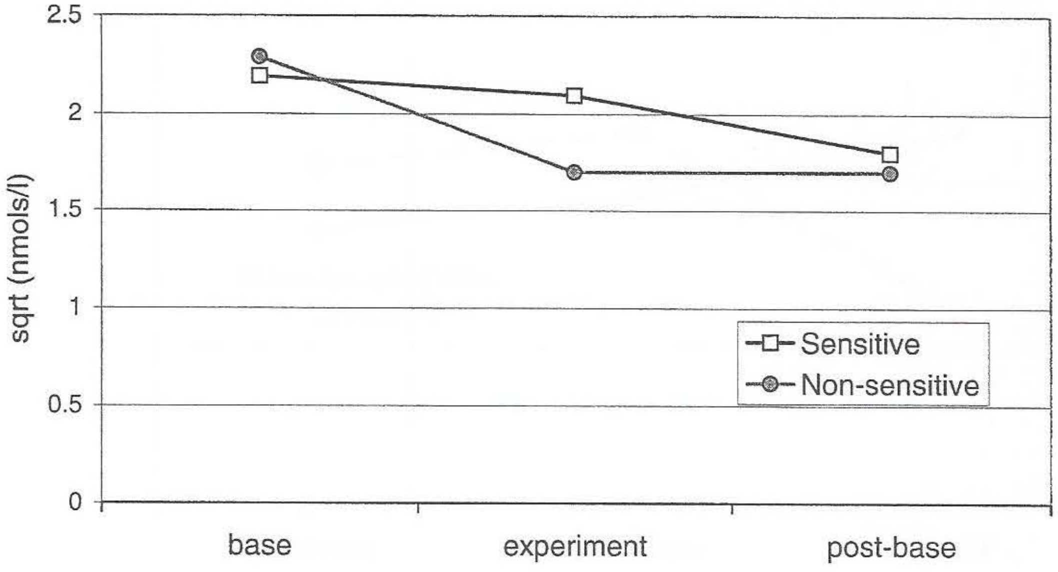

Figure 3. Average values of cortisol during base, experimententał period and post-base for subjects sensitive and non-sensitive to noise in general, for the low frequency noise condition.

3.2 Subjective estimations Over all means of the subjective rating of stress for all subjects across both noise conditions are plotted in Figure 2. The main effect for period was highly significant (F=24.80; df=2,50; p<.001). Orthogonal comparisons shows that stress was elevated during experimental periods compared to base points (t=6.57; p<.001), but also still elevated post-base compared to pre-base (t=4.01; p<.001). No other effects were significant: thus increased stress reporting during the experiment does not appear to be modulated by noise condition or noise-sensitivity of the subject.

Analysis of differences in stress reporting among the three occasions during the experimental period itself revealed over all effects (F=15.71; df=2,50; p<.001). Stress reports were relatively high on the first trial measure (M =2.3; se=.13), fell for the middle trial measure (M=1.8; se=.13), but then very significantly increased (M=2.5; se=.15) for the final trial measure (t=6.20; p<.001). There were no significant effects of noise condition or noise sensitivity.

The low frequency noise was on average rated as more annoying then the reference noise (2.47 versus 2.00; F(1,31)=9.922, p<0.005). No significant difference between noises was found when the subjects were classified into general noise sensitivity.

Low frequency noise was on average considered to impair the working capacity more than the reference noise (3.4 versus 2.6; F(1,31)=4.649, p<0.05). When the data was subdivided into general noise sensitivity, the noise difference was no longer present.

3.3 Correlational Analysis of Cortisol and Stress Reporting. In order to examine a fundamental assumption of the study that cortisol activity reflects stress, we computed base corrected cortisol and self-report stress scores for both noise conditions, expressing experimental period as percentage above or below mean base. The correlation between stress and cortisol for both noise conditions was positive in direction. However the correlation was moderately large and statistically significant for the low frequency noise condition only ($r= 0.40$; $n=27$; $p<.05$). The correlation for the reference noise was $r= 0.19$ and not significant.

4. Conclusion

The major hypothesis in the study was that exposure to low frequency noise would induce a stress situation in the test person while performing a performance task. Support for this hypothesis could be found for subjects sensitive to noise in general, while no noise effects could be found for subjects non sensitive to noise in general.

Higher cortisol values were associated with the combination of being noise sensitive and being in a low frequency noise condition. In this same condition, cortisol was found to be a bio-marker of stress-reporting.

Acknowledgement. The project was supported by funds from Swedish Council for Work Life research (grant no 1998-06-08). The project was part of a network-program for occupational health research, funded by the Swedish Working Life Institute (97/0730).

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Occupational disease by hand-arm vibration
- Relation between characteristics of case and kind of tool -

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Summary

In statistics of workers' accidents under the Compensation Law in Japan, the number of cases of occupational disease due to hand-arm vibration in private enterprises was 2,120 from 1994 to 1997. These consisted of 712 cases (33.6%) by rock drill operation, 372 (17.5) by chain saw, 323 (15.2) by pick hammer, 241 (11.4) by concrete vibrator, 80 (3.8) by concrete breaker, 61 (2.9) by bush cutter, 50 (2.4) by chipping hammer, and 51 (2.4) by portable grinder, among others. The characteristic clinical features of vibration disease differ greatly with the kind of tool. Because each tool has its own characteristic of an engineering nature, which combined with many factors in operation at the workplace, serves to form characteristic clinical features. Nine cases from our laboratory cases were discussed in this connection.

Number of new cases of vibration disease by kind of tool in the statistics from Workers' Accident Compensation (from 1994 to 1997)

The number of new cases recognized as occupational vibration disease in a year increased from 361 in 1965 to 2,595 in 1978, and then gradually decreased to 2,120 in 1997 in private enterprises.

From 1994, new cases due to hand-arm vibration exposure were described by the kind of vibrating tools. Table 11 shows the number of cases by tool (tool No. 1 to 28) in the order of the total numbers of cases from 1994 to 1997 (1999. Ministry of Labour [1]).

Nine cases of occupational vibration disease treated in our laboratory

From 1965 to the 1980s, many workers suffering from vibration injury visited our laboratory for diagnosis and treatment. In the 1960s and 1970s, without preventive work regulation, many cases had severe symptoms, and their prognoses were not so good in spite of taking long rest and receiving appropriate therapy.

From cases recognized as occupational disease under the Workers' Compensation Law, we selected nine cases (one case per tool) treated in our laboratory as shown in Table 2. Their case number is the same as their tool number corresponding to the tool used in Table 1.

In order to analyze the relation between tool and the characteristics of vibration disease, we made Tables 2-1 and 2-2. Table 2-1 includes case No., tool, risk factors in tool and tool operation. Tool No. corresponds to Tool No. in Table 1. Table 2-2 includes case No., name, age, tool (Tool No.), R.P. (severity in Raynaud's Phenomenon), dysfunction at first diagnosis

Table 1: Number of cases recognized as occupational vibration disease (from 1994 to 1997) (Workers' Accident Compensation Statistics, Ministry of Labour in Japan)

Tool No.	Tool	Main industry, in which cases occurred	Number of cases				Total number of cases from 1994 to 1997
			'94	'95	'96	'97	
1	Rock drill	Mine and construction	144	192	190	186	712 (33.6%)
2	Chain saw	Forestry	138	132	127	151	372 (17.5)
3	Coal pick hammer	Mine and construction	62	87	71	103	323 (15.2)
4	Concrete vibrator	Construction	36	64	68	73	241 (11.4)
5	Concrete breaker	Construction	11	20	24	25	80 (3.8)
6	Bush cutter	Forestry	14	16	16	15	61 (2.9)
7	Chipping hammer	Stone and metal	21	10	6	13	50 (2.4)
8	Portable grinder	Metal	10	17	13	11	51 (2.4)
9	Sander	Metal	12	5	7	10	34 (1.6)
10	Vibration drill	Metal	5	6	7	3	21 (1.0)
11	Impact wrench	Metal and automobile	5	4	6	3	18 (0.8)
12	Pedestal grinder	Metal	4	8	4	0	16 (0.8)
13	Portable tight tamper	Railway	2	1	2	6	11 (0.5)
14	Sand rammer	Metal	1	3	4	0	8 (0.4)
15	Electric hammer	Metal	2	1	2	0	6 (0.3)
16	Scaling hammer	Metal	3	0	1	0	4 (0.2)
17	Engine cutter	Metal	0	3	1	0	4 (0.2)
18	Jigsaw	Metal and wood	0	2	1	1	4 (0.2)
19	Riveter	Automobile, ship building and construction	0	0	1	2	3 (0.2)
20	Swing grinder	Metal	1	0	0	2	3 (0.8)

Table 1: Number of cases recognized as occupational vibration disease (from 1994 to 1997) (Workers' Accident Compensation Statistics, Ministry of Labour in Japan) (Continued)

21	Hand hammer	Metal and wood	1	0	1	0	2 (0.5)
22	Chisel with multi-needle	Metal	0	1	0	1	2 (0.5)
23	Caulking hammer	Metal	0	0	0	1	1 (0.3)
24	Baby hammer	Metal	0	1	0	0	1 (0.3)
25	Portable barker	Wood	0	0	0	0	0
26	Floor grinder	Construction	0	0	0	0	0
27	Vibration shear	Metal	0	0	0	0	0
28	Others		3	5	4	5	17 (4.3)
Total (from 1994 to 1997)			475	578	555	512	2120 (100.0%)

(severity of dysfunction in vascular, neural, muscular, joint systems and finger dexterity), prognosis in observed term after stopping vibration exposure (severity of total features of case). The symbols indicate the severity of symptoms: (+++) is severe in symptom, (++) is moderate, (+) is light and (-) is slight or none. (/) indicates not observed after stopping vibration exposure.

Cases in Table 2 are described in the order of severity, firstly in R.P., secondly in vascular dysfunction, and thirdly in neural dysfunction.

Relation between risk factors in tool and tool operation, and characteristics of dysfunction and prognosis in nine cases

In Case 1 (engine chain saw), Case 2 (pneumatic rock drill1), and Case 3 (pedestal grinder), the risk factors in tool and tool operation include high vibration level, long-term exposure in a day and over years, cold environment (and cold by expansion of exhaust compressed air in Case 1), heavy weight of tool, tight gripping, bending posture and both hand gripping. Cold in Cases 1 and 2 is from atmosphere and expansion of exhausted compressed air, and in Case 3 from atmosphere and ventilation. Their dysfunction appeared in all items in Table 2, that is, R.P., dysfunction in vascular, neural, muscular and joint systems, and loss of dexterity. Their severity ranged from grade +++ to + in both hands. Their prognoses in 10 years after stopping vibration exposure did not show improvement.

In Case 3, muscular dysfunction was more severe than in Cases 1 and 2. It was caused by strong strain in tightly gripping and supporting cutter tip by both hands, under high vibration while attempting to avoid damage to the cutter edge. This case is described in detail in the next section.

Case 4 operated a rock drill and chipping hammer. The risk factors were cold environment and cold by exhaust compressed air, long hours of exposure (drill for 3 hours and pick for 5 hours), tight gripping of the pneumatic drill with both hands, and tight gripping of the chisel by the left hand while supporting the handle of the chipping hammer by the right hand. His dysfunction appeared severe in chisel gripping on the left side and moderate on the other side.

Case 5 operated a coal pick hammer and portable grinder. The risk factors were different from other cases. He experienced R.P. after exposure to vibration, firstly long term in a warm condition, and secondly short term in a cold condition. This case is described in detail in the next section.

Case 6 operated a concrete immersion vibrator. The risk factors were cold environment, moderate vibration level and long-term vibration exposure, tight gripping of the shaft usually by the left hand, sometimes by the right hand. His dysfunction appeared severe in R.P. and dysfunction in many systems on the gripping side, and moderate on the other side without R.P.

Case 7 operated a vibration drill to make a hole in metal molds for wire processing. Risk factors included cool environment in factory and cold in town, moderate level vibration exposure, and tight gripping of the shaft by the right hand while supporting by the right elbow on a table. Thus, muscle strain in the hand, arm and shoulder on the right side was strong. Dysfunction appeared only in gripping and supporting on the right side.

Case 8 operated a sand rammer to tamp sand into molds. The risk factors were cool environment in factory and cold in town, moderate level vibration, long-term exposure, and gripping by the left hand. Dysfunction lightly or moderately appeared in R.P and other systems on the gripping side.

Case 9 operated an impact wrench to set or loosen screws in molds for concrete piles. Risk factors included cold environment and cold by exhaust compressed air, high vibration level and shock, exposure for long hours per day and many years, tight gripping by both hands. Dysfunction appeared severely in many systems, but without R.P. Severe muscle cramps in fingers and arms occurred frequently. Shock vibration may be the cause of muscle cramps.

Cases 3 and 5 with different risks in operation

Case 3. N.N. aged 39. (Tool No. 11)

Occupation. At 22 years old, he worked in a lathe factory. He had two kinds of job, operation of a lathe (6 hrs per day) and grinding tips of lathe cutters by a pedestal grinder (2 hrs per day) for 3 years. The vibration level was very high.
Grinding cutter tips gradually increased 4 to 5 hrs for 3 years. The company changed from an alternative job system to a full job system for high efficiency. His grinding hours became 8.5 hours per day. In the grinding room, the ventilation fan worked hard to exhaust the cutting dust, so he always felt a chill during grinding.

History of symptoms. The work load in lathe operation was light. However, grinding cutter tips put a heavy strain on his finger, hand, arm and other parts of his whole body, because in order to keep the tips steady against vibration and to avoid damage to the cutter edge he had to strain forward in a bending posture. Also, in the grinding room, he always felt chills in his hand and leg during grinding.
By increasing grinding hours, he experienced weariness in arm, shoulder, neck and back, and coldness of hand, as well as numbness, tingling and cyanosis in finger, pain in shoulder, and stiffness of muscle in neck and back. Feverishness and pain in his muscles at night disturbed his sleep.
Severe chills in his hand and frequent attacks of white finger (R III, L III) appeared after 1.5 years from beginning the full-job system. He then stopped his work and visited our laboratory.

Physical examination. Vascular and neurological findings; 1) attack of white finger, 2) decrease of peripheral circulation, 3) decrease in sensibility in upper extremities, 4) decrease of grip, pinch force and tapping ability in both hands, 5) stiffness and pain in muscles of arm, neck, shoulder and back, 6) radiation of pain from nerve plexus by compression. Findings in blood and urine chemistry, circulatory function test, X-ray test and orthopedic test for discernment were all normal. No other diseases were noted.

Diagnosis and compensation. The diagnosis was hand-arm vibration syndrome due to grinding cutter tips. He took a rest and hospital therapy covered by Workers' Accident Compensation.

Prognosis. After stopping exposure to vibration, he was treated by thermal and medical therapy in a hot spa hospital for a half year. Hot spa therapy proved effective in reducing his symptoms. After leaving the hospital, he moved to a warm city and took a light job. In the fourth winter season after leaving the hospital, he experienced a mild white finger attack. After 5 years, the stiffness in his muscles disappeared. But the loss of grip force, pinch force, and sensorineural function remained.

Table 2-1:Risk factors in tool and tool operation
(Tool No. in Table 2 corresponds to Tool No. in Table 1)

Case No.	Tool (No. in Table 1)	Risk factors in tool and tool operation
1	Engine chain saw (2)	1) tree felling on mountain slope, 2) cold (-5 to 5°C) 3) high level & long-term vibration exposure (5 to 7 hrs/day, 12 yrs), 4) bending posture, with heavy weight (15 to 12 kg) 5) both hand gripping
2	Pneumatic rock drill (1)	1) dig out limestone in quarry, 2) cold (-3 to 6°C), cold exhaust air 3) high level & long-term vibration exposure (5 to 7 hrs/day, 15 yrs), 4) bending posture, with heavy weight (12 kg), 5) both hand gripping
3	Pedestal grinder (11)	1) grinding edged tool, 2) cold (air: 0 to 5°C, and blower's cold wind), 3) high level & long-term vibration exposure (5 to 7 hrs/day, 10 yrs), 4) tightly gripping cutting tip, with muscle strain in whole body, with bending posture, 5) both hand gripping
4	Rock drill (1) & Chipping hammer (7)	1) mining stone in quarry, 2) cold (0 to 5°C), cold exhaust air 3) high level vibration, long hrs exposure (pick 5, drill 3 hrs/day, 3.5 yrs 4) tightly gripping chisel by L hand, supporting R hand, weight (5 kg) 5) gripping rock drill with both hands (12kg)
5	Coal pick (3) (A) then Portable grinder (8) (B)	A. 1) mining coal under ground, 2) hot in mine (30 to 32°C)(safety factor) 3) moderate level & long term vibration exposure (5 to 6 hrs/day, 11 yrs 4) bending posture forward with coal pick (12 kg), 5) both hand gripping B. 1) grinding in foundry, 2) cold (0 to 5°C) in factory & home, 3) moderate level & short term vibration exposure (4 to 5 hrs/day, 1.5 yrs) 4) bending posture with weight (5 kg), 5) both hand gripping
6	Concrete immersion vibrator (4)	1) stirring non harden concrete in building site, 2) cold (0 to 6°C) 3) moderate level & long-term vibration exposure (5 to 6 hrs/day, 9 yrs) 4) tightly gripping shaft by L hand, supporting by L hand, weight (3.5 kg) 5) advanced age
7	Vibration drill (10)	1) make hole and grinding hole in metal parts for electric wire making, 2) cool in factory (5-10°C), cold in town (0 to 8°C), 3) moderate level vibration exposure (4 to 5 hrs/day 10 yrs), 4) tight gripping, shaft by R hand & supporting by R elbow on table, 1.5 kg
8	Sand rammer (14)	1) tamping sand in mold, 2) cool in factory, cold in town (-5 to 5°C), 3) moderate level & short-term vibration exposure (3 to 5 hrs/day, 5 yrs),, 4) tightly gripping shaft of tamper by L hand, weight 2.5 kg
9	Impact wrench (12)	1) closing & opening mold of concrete pile, 2) cold (3~6°C), exhaust air, 3) high level and long-term shock vibration exposure (6~8 hrs/day, 6 yrs), 4) supporting by left hand & gripping accel lever by R hand, weight 4.6 kg, 5) tightly gripping by both hands

Table 2-2:Dysfuntion at first diagnosis and prognosis after stopping vibration exposure (+++: sever dysfunction, ++: moderate, +: light, -:slight or non, /:without observation)

Case No. Name Age	Tool (No. in Table 1)	R. P.	Dysfunction at first diagnosis					Prognosis in observed term (years), after stopping vibration exposure			
			Vascular system	Neural system	Muscular system	Joint system	Finger dexterity	0-5	5-10	10-15	15-
1 T. N. 48	Engine chain saw (2)	R+++ L+++	+++ +++	++ +++	++ ++	+ ++	+++ +++	+++	++	+	-
2 T. K. 45	Pneumatic rock drill (1)	R ++ L ++	++ ++	++ ++	++ ++	+ ++	+ ++	+++	+	/	/
3 N. N. 39	Pedestal grinder (11)	R ++ L ++	++ ++	+++ +++	+++ +++	++ ++	++ ++	++	+	/	/
4 Y. N. 34	Rock drill (1) & chipping hammer(7)	R + L ++	++ +++	+ +++	+ +	- +	- +	self-employed worker, unable to stop operation, dysfunctions continued			
5 M. N. 44	Coal pick, (3) then Portable grinder (8)	R + L +	+ +	+++ +++	++ ++	+ ++	+ ++	++	+	/	/
6 H. N. 62	Concrete immersion vibrator (4)	R - L +	++ +++	+ +++	+ +++	- ++ +	- ++	++	/	/	/
7 T. O. 38	Vibration drill (10)	R + L -	++ -	+ -	++ -	+ -	+ -	/	/	/	/
8 E. I. 40	Sand rammer (14)	R - L +	- +	- +	- +	- +	- +	+	/	/	/
9 A. N. 45	Impact wrench (12)	R - L -	+++ +++	++ ++	++ cramp ++ cramp	+ +	+ +	++	/	/	/

Case 5. T.N. aged 32. (Tool No. 3 & 8)

Occupation. At 25 years old, he worked in an underground coal mine in Kyushu (in southwest Japan). He operated a coal pick hammer for 8 hours a day for 11 years. The coal pick hammer weighed 7.2 kg and delivered 1,230 strokes per minute. Atmospheric temperature in the workplace ranged from 30 to 32oC in all seasons. His living area was warm in winter. After the closing of the coal mine, he moved to central Japan in autumn. It was cold in winter. He operated a portable grinder in a foundry, grinding castings for 8 hours a day.

History of symptoms. In the coal mine, he felt weariness and pain in fingers, arms and shoulder joints after coal pick operation, and slight hand chills in winter. Three months after moving, he felt chills in daily life and work. Soon, he felt pain and tingling in fingers and hands after operation and during the night. In the second winter, he noticed three white fingers on his left hand (skillful side) and then two in the right. R.P. attacks were frequent. He lost dexterity in finger movement. The pain and tingling in his hands and arms disturbed his sleep.
The hospital doctor doubted that his symptom originated in exposure to vibration in grinding work. But the Labor Standard Office also had its doubts: "Does such short-term exposure in grinding work cause severe vibration syndrome? Are there any other possible causes for his symptoms?"

Physical examination. Vascular and neurological findings were as follows; 1) attack of white finger, 2) decrease of peripheral circulation, 3) remarkable decrease in sensibility in extremities, especially upper extremities, 4) decrease of grip and pinch force and tapping ability in both hands, and 5) stiffness in muscles of arm, neck, shoulder and back. Findings in blood and urine chemistry, circulatory function test, X-ray test and orthopedic test for discernment were all normal. Other diseases were not noted.
Discussion;
Judging from his complaints concerning operation of the coal pick and the hand grinder, it may be supposed that exposure to vibration and the heavy weight of the pick hammer affected his peripheral vascular, sensory neural and musculoskeletal systems. But he was not aware of such dysfunction in daily life without fine touch and movement. It may be suspected that exposure to vibration created hypersensitivity of the blood vessels in his finger to cold, but warm conditions in daily life and work did not induce any vascular contraction due to the cold. After moving to central Japan and engaging in grinding, the combined effect of cold and vibration might have rapidly intensified, causing hypersensitivity of peripheral blood vessels to cold on the basis of the exposure effect in the coal mine, in spite of the short-term exposure to vibration in the foundry. The cold encountered in daily life then invited an attack of white finger.

Diagnosis and compensation. The diagnosis was hand-arm vibration syndrome due to pick hammer operation. He took a rest and hospital therapy under the Workers' Accident Compensation Law.

Prognosis. After stopping exposure to vibration, he was given thermal and medical therapy in a hospital setting. After three months, he changed jobs. His symptoms very slowly disappeared over four winter seasons. In the fifth winter, he experienced a mild white finger attack. But the coldness in his hands, and loss of finger dexterity remained. His sensorineural dysfunction failed to disappear.

Discussion

Complex relation among risk factors in tool and tool operation;

The risk factors causing vibration disease in tool and tool operation in the cases described above were high vibration level and shock, long-exposure (hours per day, years), heavy weight of tools, tight gripping of the handle or shaft or processing material, bending posture in operation, cold conditions (in working or residential environment, cold from greater exhaust compressed air, cold air current by ventilation). The effects of these factors always appear in such a complex manner and so unquantitatively that diagnosis and recognition of occupational vibration disease and epidemiological research works often face difficulties. The relation between the risk factors and the characteristics in nine cases is as follows.

Relation between risk factors in tool and characteristics of cases with vibration disease;

Vibration is the most essential risk factor, and it is evaluated by the frequency weighted acceleration level in ISO guideline (1986)[2] for prevention of vibration injury on the basis of the relationship between vibration exposure dose and incidence of R.P. Relations between vibration exposure dose and dysfunction of other vascular, neural, muscular, skeletal systems, dexterity system and subjective symptoms have been reported by a few researchers (1992 Lundstrom[3], 1994 Bovenzi[4], 1996 Yamada[5]).

Lengthy exposure to vibration for a day and over years intensifieseffects of vibration. Exposure hours are 5 to 6 hours/day in Cases 5 and 6, 5 to 7 in Cases 1, 2 and 3, and 6 to 8 in Case 9. Exposure years are over 10 years in Cases 1, 2, 3, 5, and 7. Their symptoms were severe. In Case 4, exposure hours were very long (pneumatic chisel 5 hours, rock drill 3 hours a day), and severe symptoms resulted in the short term (3 years).
Cold is an important factor, firstly because it intensifies vascular dysfunction and secondly causes low nutrition in tissue and stagnation of tissue fluid, resulting in tissue degeneration (in nervous and connected tissues).
Vibration exposure together with cold readily causes hypersensitivity of blood vessels to cold, and temperature lower than 10°C causes R.P. In eight cases, all but Case 5(A) worked and lived under temperature conditions lower than 10°C in winter, and many cases under lower than 5°C. The R.P. was severe in Cases 1, 2 and 3, moderate in 4 and 5, and light in 6, 7 and 8. Case 5, who was exposed to vibration for a long term in warm conditions and then for a short term in cold conditions, is described in the earlier section.
Case 9, exposed to a high vibration level, has no R.P., but suffers from severe vascular dysfunction. From this result, it may be suspected that the mild temperature in his factory and living area delayed his first attack of R.P., but R.P. will appear sooner or later.

Bearing weight in a bending posture tends to intensify muscle and tendon strain in hand, arm, shoulder, neck, back and leg. Muscle and tendon strain intensified by weight decreases the blood flow in each tissue and causes dysfunction of muscles and neuromuscular apparatus. Cases 1, 2, 4 and 5 continually bore tool weights of over 10 kg.
Gripping force was large in all cases. Case 3 gripped very tightly the cutter tips and suffered a form of stiffness and pain in the muscles throughout his body. Cases 6, 7 and 8 gripped the tool only by one hand, and were affected by R.P and dysfunction in many systems only on the gripping side.

The appearance of the characteristic clinical features in the nine cases showed a great difference. These differences were caused by a combination of frequency-weighted vibration level and other risk factors. In the diagnosis and recognition of occupational vibration disease and in the analysis of epidemiological research among workers exposed to vibration, it is recommended that discussion be conducted with reference to the relation between characteristics of the case and the risk factors in tool and tool operation.

Conclusion

The relation between risk factors in tool and tool operation, and characteristic clinical features of cases was discussed. It is recommended that this discussion be conducted in diagnosis and epidemiological research.

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