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SUMMARY

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Letter from the Editor

Welcome to the fifth edition of Acoustics in Practice. The journal serves the many practioners members of the European Acoustics Association's member societies who work in the many areas of applied acoustics including consultancy, policy making, regulation and manufacturing. The range of papers in this edition again shows how acoustics plays a significant part in virtually all aspects of modern life. The ability to accurately predict the impacts of noise and vibration sources in the community and to understand the people's reaction to those noise sources is vital to ensuring our wellbeing and enjoyment of the environments that we live in.

One of our journal's objectives has been to disseminate knowledge and experience gained in any one of our member countries across the entire European membership. All too often authors present their findings at local and national conferences and these papers are not accessible to members in other countries. We encourage these authors to publish their work in Acoustics in Practice to gain a Europe-wide and permanent web presence for their work. We can all learn from the experience gained in other countries and different pressures mean that other countries find that different issues emerge when working with the same topic. This is demonstrated by the paper we publish on amplitude modulation in wind farm noise. In the UK this has been a hot topic for several years while in other European countries it is hardly discussed and other issues dominate the debate there. We are keen to publish papers on this topic and also the other issues concerning wind farm noise in other European countries. This is, of course, true of all of the papers we publish as our purpose is to encourage debate and learning on all areas of practical acoustics.

The editorial board can be found in this issue immediately after the technical papers. Offers from anyone wishing to join the editorial board would be most welcome. We would like the board to cover all areas of acoustics, but also represent as many as possible of the EAA member societies.

Colin English
(AiP Editor in Chief)

Automatic Recognition Technique for Construction Noise Sources*

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ABSTRACT

This paper explores the possibility of identifying construction noise sources from general urban background noise, based on recently developed techniques of sound source recognition. Using the large construction project of London Bridge Station redevelopment as a case study site, sound recordings were made which represent typical sound sources in that area, with the sound pressure levels measured simultaneously. Based on the analyses of the recordings with objective measures, including a range of acoustic/psychoacoustic parameters, the noise sources in the recordings were automatically identified according to a number of classification conditions. The recognition accuracies varied from 78% to 94%, depending on the construction noise type.

Keywords: sound source recognition, soundscape, construction noise

1. INTRODUCTION

The subjective evaluation/preference of soundscapes, i.e., holistic sound environment [1], operate on the basis of identification of physical sound sources [2]. Even with the same sound level, people's degree of tolerance varies among different types of environmental sound, such as sounds from nature or transport [3].

In construction projects, although conventional noise monitoring and predicting on sound level have been often taken, complaints have still been received concerning the construction and its related transportation noise from the local residents. Moreover, the noise might also result from the nearby transportations and other construction sites, which brings difficulties in the noise management and control. Thus, there is a recognised need to develop innovative techniques for monitoring the holistic sound environment and recognising automatically the noise sources, in order to help noise management and control.

This paper explores the possibility of automatically identifying construction noise sources from general urban background noise, based on the techniques of single sound source recognition developed in the previous research of the authors [4-6]. Also, it studies the possibility of the technique in wide practical applications, that is, it looks for simple algorithm and procedure that do not have very high requirements for the monitoring and processing systems. This paper uses the large construction project of London Bridge Station (LBS) redevelopment as a case study site.

2. LITERATURE REVIEW

A number of studies have aimed to build a system that can become the basis for an automatic analysis tool by identifying sound events in soundscapes. Basically, sound recognition (both for speech/music and environmental sounds) is achieved by two phases: first feature extraction, followed by classification. The feature extraction (or say parameterisation) stage produces a set of characteristic features for sound to reduce the complexity of the data before it reaches the classifier. The classification stage then recognises the sound based on the extracted features [7].

For single environmental sound recognition, Cowling and Sitte [7] comprehensively compared the different techniques that were typically used in speech and musical instrument recognition in their

* Part of this work was published in [6].

suitability for environmental sound identification. From the combinations of feature extraction techniques (such as frequency extraction, homomorphic/ Mel frequency/ Bark frequency cepstral coefficients, linear prediction cepstral (LPC) coefficients, perceptual linear prediction (PLP) features, short-time Fourier transform (STFT), fast (discrete) wavelet transform (FWT), and continuous wavelet transform (CWT)) and classification techniques (such as dynamic time warping (DTW), hidden Markov models (HMM), learning vector quantization (LVQ), self-organising maps (SOM), artificial neural networks (ANN), long-term statistics, maximum likelihood estimation (MLE), Gaussian mixture models (GMM), and support vector machines (SVM)), Cowling and Sitte found that the combination of CWT or Mel frequency cepstral coefficients (MFCCs) with DTW produced the best results, with a classification rate of about 70%.

For real-world environmental sounds, i.e., multiple sound sources that are mixed together, Bunting et al. [8], in the project of instrument for soundscape recognition, identification and evaluation (ISRIE), used time-domain signal coding (TDSC) combined with LVQ network, and employed a source separation algorithm prior to the feature extraction and classification stages. The accuracy varied among sound categories, and was not high for some categories. Krijnders et al. [9] used a segment based on time-frequency cochleogram prior to the feature extraction and classification stages and also a dynamic network creating expectancies of sound events based on context information to improve the classification. The accuracies were generally not high, with F-measure of 0.45 and precision of 0.42. For recognition of soundscapes holistically, that is without the identification of constituent sound sources, Aucouturier et al. [10, 11] used the "bag-of-frames" approach, which represented signals as the long-term statistical distribution of frame-based MFCC vectors, and GMMs, and proved a precision of 0.74.

In contrast to these methods, in a research of Yang and Kang [4, 5] of single environmental sound identification, without using the MFCCs for feature extraction as in majority of the above studies, a range of psychoacoustic, music, and 1/f noise indicators were considered, such as loudness, pitch, and fluctuation strength [12]. While MFCCs represent the spectrum of spectrum of signal on Mel frequency scale [13], they may be more suitable for feature extraction of speech and music rather than environmental sounds, since speech/music often consists of harmonic tonal components, whereas environmental sounds often consist of broadband noise. Combined with machine learning or mathematical models for classification, such as discriminant function analyses and ANNs, the prediction accuracies were above about 98% for the three natural sound categories, i.e. water, wind, and birdsongs, and one urban sound category considered (when fountain were labelled as water sound in one natural sound category). The method achieved high prediction accuracies, although the accuracies were not directly comparable across the different studies, since the sound samples and statistic methods of accuracy calculation differed.

In this paper, this sound source identification method is further developed and tested for recognition of specific sound sources in the real, complex environment, which have multiple sound sources mixed together, with a particular focus on construction noise sources.

3. METHODS

3.1. Framework

For the real-world environmental sounds, in this paper, before the feature extraction and classification stages, a sound signal is first decomposed into successive frames of short duration. It is assumed that in the short duration of time (frame), the sound events remain relatively constant. Then the feature extraction and classification are applied based on each frame. The procedure of the whole sound source recognition method is shown in Figure 1.

In this paper, the frame length of 1 minute with half overlap is used. The duration or length of frame is determined by the acoustic characteristics of the sound types to be identified, by examining the variation of spectrum with time of the sounds, as discussed following in Section 4.1. The 1-min duration is generally

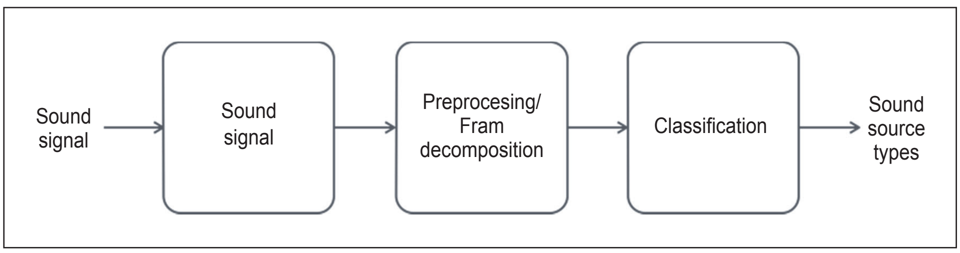

Figure 1. *Sound source recognition method.*

long enough to cover the dynamic characteristics of the sound events, and also shorter than the duration of each type of sound event.

3.2. Recording

Two sets of recordings of soundscape in the construction area were analysed, which include the sound pressure levels and sound recordings at some particular receivers in or around the construction site, made with professional microphones and recorders. The first set of recordings has frequency responses from about 10 to 2800Hz in the frequency domain, mono channel, and were monitored all day long and stored in the digital format of AAC, at the sample rate of 22,050 Hz in the time domain. The second set of recordings has higher quality, with frequency responses from about 10 Hz to 20 kHz and stored in the WAV digital format, at the sample rate of 44,100 Hz. In this research, only mono-channel recordings were used, which did not have high requirements about the recording equipment and procedure.

From the large database of recordings, in order to search for the appropriate indicators of feature extraction, 23 1-min recording segments, which represent the typical sound sources in that area, were selected and clipped as samples for the analyses. The main sound types include demolition, vibration machine, public address (PA) system of the railway station, airplane, piling, heavy trucks, and background noise. In each recording segment, one or two dominant sound sources can be heard.

To develop the classification method and test the recognition performance, approximately 14-hour recordings were used. For testing reversing alarm and demolition sound, 10 approximately 1-hour recordings were selected as samples from the database provided by Costain. For testing piling sound, about 2-hours recordings made by the authors were used, and so were for testing heavy truck sound. Each of the recordings was then decomposed by successive frames (frame length of 1min and half overlap) for further processing and recognition. The total number of frames used for examining each type of sound is shown in Table 1.

Table 1. Recognition accuracies of reversing alarm and demolition sound

	Signal processing		
	Correct	Total	Percen-tage
Non reversing alarm	855	942	90.8%
Reversing alarm	200	237	84.4%
Total	1055	1179	89.5%
Non demolition	745	983	75.8%
Demolition	169	196	86.2%
Total	914	1179	77.5%
Non piling	193	204	94.6%
Piling	30	33	90.9%
Total	223	237	94.1%
Non heavy trucks	165	187	88.2%
Heavy trucks	26	36	72.2%
Total	191	223	85.7%

3.3. Sound identification through listening

The sound source types of recordings were firstly identified to be compared with the automatically identified types. For the recordings made by the authors, the sound sources or events were documented while recording was made. For the recordings provided by Costain, for which this information was not available, the sound sources in each 1-min recording segment and in each frame of the recordings were identified by one of the authors through listening. The sound recordings were reproduced with Sennheiser HD 558 headphones, from a stationary computer. The sounds were presented using ArtemiS software package [14], and could be replayed as many times as needed while identifying the sound event types. Within a frame, the most dominant sources (maximum 3) were identified.

4. AUTOMATIC SOURCE RECOGNITION

4.1. Indicators for feature extraction

To look for the indicators of feature extraction, the variation of spectra of the 1-min recording segments are analysed using ArtemiS [14]; parts of the results are shown in Figure 1. By analysing the spectra with time, some initial results of the characteristics of the different sound types are drawn. For example, in Figure 1 (a), the alarm sound of a reversing construction vehicle have distinct pure tone component, indicated by the horizontal discontinuous line in the frequency range between 1k and 2k Hz. Demolition sounds are characterised by sudden changes in intensity, which happen simultaneously in all frequencies, indicated by the vertical lines in the spectrum. The sound of PA system, in Figure 1 (b), has its particular pattern in spectrum with time around the frequency range of 1k Hz, the intensity changes asynchronously at different frequencies in this range.

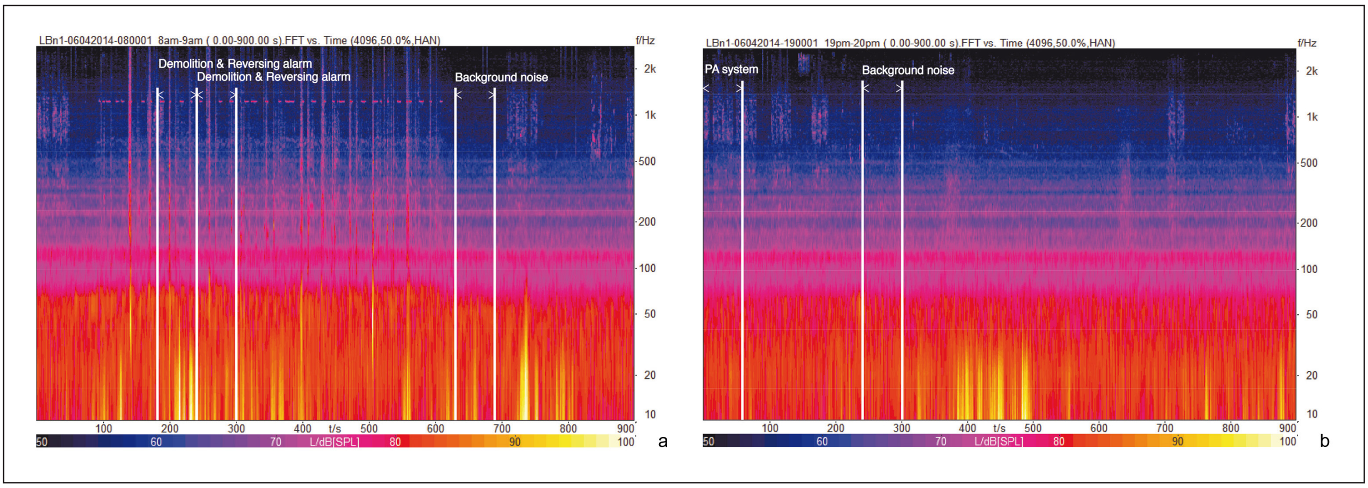

Figure 2. Spectra vs. time of two sound recordings (a) and (b). Each figure presents 15 min in duration of a recording, in which the 1-min recording segments are at the indicated areas between the two vertical white lines.

To reflect the respective characteristics of the different sound types, a number of indicators are then selected/developed. A series of indicators are examined, which include sound pressure level (SPL), A-weighted SPL, and psychoacoustic parameters, such as loudness, sharpness, tonality, pitch, and rhythm, calculated using ArtemiS [14] or Matlab with MIRtoolbox [15]. The results show that among the indicators, the conventional acoustic/psychoacoustic parameters may not show the differences of the characteristics of the different sound types, but some specific indicators do, such as peak frequency in spectrum, average amplitude of peaks of spectrum, peak (event) density in spectral flux [16], average value of peaks in spectral flux (attack intensity), maximum peak of spectral flux, and periodicity. Taking the sound sources in Figure 1 for example, among these sounds, only reversing alarm sounds have distinct peak in spectrum at about 1.2k to 1.4k Hz. Demolition sounds have high average values of peaks in spectral flux, whereas PA system and background noise have relatively low average values. More detailed results are available upon request.

4.2. Automatic classification

The method for the classification stage is developed and tested using large size of samples. The indicators developed above are calculated for each frame of the recordings. Since multiple sound sources can be identified for each frame (that is, each frame is not restrict to one type of sound), each of the sound sources to be identified is estimated respectively whether or not happened in each frame. To identify each type of sound, one indicator is used here. Instead of machine learning models used in the previous research, which are computationally expensive, simple evaluation of the value ranges of the results of the indicators according to certain classification rules is used for the automatic recognition of sound sources. For example, a sample frame is identified to have reversing alarm sound if the indicator related to distinct peak in spectrum reaches a certain value.

With these methods, the sound sources identified in each sample frame are compared with those identified by human. The numbers and percentages of correctly identified sample frames are shown in Table 1. Here, the accuracies of four sound types are shown, i.e., reversing alarm of construction vehicles, sounds of demolition, piling, and heavy trucks, all of which are arresting and annoying noises in construction sites. For each sound type, the table presents both the numbers/percentages of correctly identified frames containing a particular sound type and of frames not containing that sound type. Overall, it can be seen that the accuracy of recognition is generally high, which is 90% for identifying reversing alarm, 78% for demolition sound, 94% for piling sound, and 86% for heavy truck sound.

There might be a number of possible causes for the amount of recognition error. First, a very few sound events, which are not to be identified in this paper, might have similar characteristics to the above sound types in the indicators used for processing. For example, beep sound from a vehicle and reversing alarm both have prominent peaks/peak in spectrum, although they can be distinguished with additional indicators. Second, the characteristics of a sound source to be identified in the indicators might become unobvious and tend to be masked in some frames, since its loudness may be relatively small compared to the other sound sources or background noise, or its duration is short in certain frame. Third, as only the most dominant sound types (maximum three) are identified through human's listening in a frame, the judgment of human may be uncertain sometimes.

5. CONCLUSIONS

In this research, a number of typical construction noise sources have been identified from the real, complex environmental sound. This research used a number of methods different with those in the previous studies of environmental sound recognition. First, prior to the feature extraction and classification stages, without a source separation algorithm, this paper processed the environmental sounds directly by decomposing signal into successive short duration frames, and identified the sound sources within each frame, based on the assumption that sound events remain relatively constant in a short duration of time. Second, for the feature extraction, different with previous methods that mainly used MFCCs as indicators, the paper applied a range of specific acoustic/psychoacoustic and music related indicators, since MFCCs may be more suitable for speech and music that often consist of harmonic tonal components rather than environmental sounds, which often consist of broadband noise. Third, for the classification stage, simple evaluation of the value ranges of the result of the indicators was used in this paper, which is much more computationally inexpensive than machine learning algorithms that have been frequently used for recognition tasks, and thus more feasible for large-scale industry applications.

Using the methods, the accuracy of the recognition of a number of typical construction noise sources is high, based on the case study site of the construction project of LBS redevelopment. The accuracy is 90% for reversing alarm of construction vehicles, 78% for demolition sound, 94% for piling sound, and 86% for heavy truck sound, even though the quality of some sound recordings used here is not very high.

The accuracy of the sound source recognition can be further increased by using more indicators for the feature extraction, narrowing the evaluation conditions for the classification stage, or using machine learning algorithms if needed. Larger sample size used for developing the indicators and classification method can also increase the accuracy.

The results show the possibility of the methods in automatic identification of sound source types from overall urban background noise, and also the potential for practical applications. It is expected that the technique of automatic recognition of environmental sounds developed in the research would help address the existing noise problems for noise control, further benefit general areas in noise monitoring/mapping, and have more applications in construction sectors and beyond.

6. ACKNOWLEDGEMENTS

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Measurements of vibrations and noise from metro trains

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ABSTRACT

Measurements of vibrations and groundborne noise from Oslo's metro trains are presented together with measurements of rail corrugation. The measurements have been performed in 12 residences. In all cases measurements of triaxial vibrations on a living room floor have been made. In some cases groundborne noise or rail surface corrugation has also been measured. Measurements have been made on a multichannel analyzer to allow simultaneous acquisition of data for all transducers. Data from at least 10 events have been collected for each house.

1. INTRODUCTION

Oslo Region Transport Engineering Section, the public company that runs Oslo's metro and tram networks, started to replace the 40 year old metro trains in 2006. The transition to the new Siemens MX-3000 trains was completed by 2010. Within a short time, increased complaints due to groundborne noise and vibrations from the metro trains were heard from the residents living close to the tracks. On this basis, a series of measurements was started in February 2011. The primary purpose of the measurements was to establish the actual situation and compare it with existing Norwegian guidelines and regulations. Measurements showing that the new MX-3000 trains did indeed give rise to a different spectrum of noise and vibrations have already been published.[1]

The performed measurements presented in this paper may, together with other investigations, become a part of the groundwork for a better understanding of the transmission of vibrations from metro trains into building foundations and living rooms in residences. Measurements of vibrations from railbound sources have a long tradition[2] as have investigations into the transfer from the ground into buildings[3,4,5]. There exists a Norwegian empirical method for calculating vibrations from railbound vehicles[6,7], and recent Japanese research[8] into vibration transmission in lightweight houses. Methods also exist for measuring vibration transmission in the ground[9], but this method is possibly a bit too comprehensive for surveys of existing situations. Vibrations may vary considerably from site to site, even at small distances.[10]

This paper deals with measured values for vibrations, groundborne noise and rail corrugation. The term groundborne noise is used for noise that has propagated as vibrations through soil or rock between the track and the house. A good general reference for groundborne noise from railbound vehicles is given by Chris Jones.[11]

2. REQUIREMENTS FOR NOISE AND VIBRATIONS

Oslo Region Transport Engineering Section tries to maintain good relations with its neighbors, and tries to control and reduce noise and vibration complaints as much as reasonably possible. As a response to the increased complaints after the introduction of the MX trains, several noise and vibration abatement measures have been put into use. It has been desirable to reduce the noise and vibrations to a lower level than required by law or regulations. The applicable regulations for existing situations and new lines are described below. These regulations apply to Norwegian conditions; other types of criteria have been suggested in other countries[12].

Norwegian regulations, for situations where both the house and the metro line have existed from before 1979, are given separately for noise and vibrations[13]. It is the objective responsibility of the owner of the noise source to comply with this set of regulations. For noise, the requirement is given as a 24-hour equivalent level. This requirement is given as an indoor level with windows and ventilation devices closed. The noise limit is $L_{Aeq24h} \leq 42$ dB. This noise limit is hardly exceeded at all along Oslo's metro lines. For vibration the requirement is given as $v_{w95} \leq 0{,}6$ mm/s in the vibration direction with the highest vibration level.

For planning of new lines, the requirements are stricter than for existing situations. The recommended values for groundborne noise for the recently reopened line Kolsåsbanen[14], has been L_{Amax}, FAST ≤ 37 dB. For airborne noise, the ordinary Norwegian regulations for indoor noise from outdoor sources[15], $L_{Aeq,24h} \leq 30$ dB and L_{5AF},night ≤ 45 dB. For vibrations the limit has been set by general Norwegian guidelines[14] to $v_{w95} \leq 0{,}3$ mm/s.

3. METHOD

It was decided to use simultaneous measurements of several parameters for each passage of a train set. The MX-3000 runs in fixed sets of 3 or 6 cars. In all cases at least 10 passages were measured. For most of the passages the average speed during the passage was measured with a stop watch.

Both vibrations and noise were measured in 1/3-octave bands in the quoted frequency ranges. For each parameter the single number value, L_{Amax},FAST for noise and v_w, SLOW for vibrations, was calculated for each passing train.

For each of the houses triaxial vibrations were measured on a living room floor. Other measurements were also performed, but this article will describe only the triaxial vibration in one point. Vibrations were measured as acceleration in dB relative to 10^{-6} m/s^2 and converted to vibration velocities. Vibration axes were defined as follows: x is the horizontal direction normal to the metro track, y is the horizontal direction parallel to the metro track, z is the vertical direction. Vibrations are presented in the frequency range 10 Hz to 1000 Hz, the maximal value with the time constant SLOW. Analysis of vibrations was performed according to NS 8176[16]. The measurements were performed using a small triaxial accelerometer. This small accelerometer has insufficient sensitivity to assure a satisfactory signal/noise ratio at frequencies below 10 Hz in some cases. However, experience has shown that there is a limited level of vibrations below 10 Hz from the metro trains to be investigated.

For each measured passage the measured maximal vibration velocity in each 1/3-octave band was multiplied by a filter factor. The square root of the sum of the squares of the weighted velocities in each frequency band is the weighted vibration velocity (v_w) for that passage. The quoted result for a point is a statistical value, $v_{w,95,}$ based on a lognormal distribution.

$$v_{w,95} = \overline{v_{w,\max}} + 1{,}8 * \sigma$$

where $v_{w,max}$ is the weighted velocity according to NS 8176[16]. A lognormal distribution of the measured data is assumed according to this standard, and σ is the standard deviation of the measured velocities. It is expected that 95% of the passing trains will give rise to a lower vibration value than the quoted $v_{w,95}$.

Groundborne noise was measured in at least one room at each location. Noise measurements were made in the frequency range 20 Hz to 20000 Hz, with the time constant FAST. The summary in table 1 give the A-weighted value as the $L_{A,max95}$ with a statistical analysis similar to that made for vibrations, but based on a normal distribution.

$$L_{A,\max 95} = \overline{L_{A,\max}} + 1{,}65 * \sigma$$

where $L_{A,max}$ is the maximal A-weighted sound level in each case, σ is the standard deviation of the measured sound pressure levels. The given value is the linear average of the dB values plus 1,8 times the standard deviation.

Rail surface corrugation was also measured on a sufficiently long stretch past each house in order to give a good measure of the rail quality on the part of the track that gave a significant contribution to groundborne noise and vibration for the house investigated. The corrugation was measured on both rails in both directions with ATP RSA. The data were recorded with a Squadriga from Head Acoustics and analyzed with their software.

4. MEASUREMENTS

The performed measurements are shown in Table 1. Measurements in February and March 2011 were made in 7 points along Oslo's metro line 1 (Frognerseterlinjen), 1 point along line 3 (Østensjøbanen), 3 points along

***Table 1.** Performed measurements*

Site	Triaxial vibrations – position	Groundborne noise – position	Ground and foundation conditions	Rail surface corrugation
1-1	Underground bathroom	Underground bedroom	Concrete structure at least 6 m below ground	Yes
1-2	Ground floor living room	Underground living room	Firm clay	Yes
1-3	Bedroom 1st floor	Underground living room	Firm clay	Yes
1-4	Kitchen ground floor	Bedroom underground	Firm clay	Yes
1-5	Kitchen ground floor	Bedroom underground	Firm clay	Yes
1-6	Living room ground floor	Bedroom underground	Firm clay	Yes
1-7	Living room ground floor	Living room underground	Probably clay	No
3-1	Living room ground floor	Bathroom underground	At least 40 meters of clay	No
4-1	Living room ground floor	Underground living room	Probably clay	No
4-2	Living room ground floor	Undergroud living room Underground bedroom	Probably clay	No
4-3	Living room ground floor	Underground living room	Probably clay	No
6-1	Living room ground floor	Underground cellar room	Probably clay	No

line 4 (Lambertseterbanen), and 1 point where several lines run on the same tracks.

4.1. Houses where vibrations and groundborne noise was measured

The houses where measurements were made are detached or vertically divided. All of these houses had a wooden or other lightweight vertical structure above ground. In two of the houses, the floor where vibrations were measured was a concrete structure cast in situ. The structure below ground is concrete or stone. Most of the houses are on sloping ground, making the definition of the floors somewhat difficult. The levels have been defined based on the side of the house facing towards the metro line. The term underground is used for rooms with the floor below ground level on the side facing the metro line. The term ground floor is used for rooms with the floor roughly on the same level as the terrain on the side facing the metro. The term 1st floor is used for rooms with the floor roughly one story above ground level on the side facing the metro. The distance is defined as the distance from the house wall closest to the track to the centerline of the metro midway between the tracks.

For the six houses where detailed results are presented, the ground conditions have been controlled against the report from tests performed during the design stage of the latest improvements to the line[17]. This is described together with the results of measurements for each of these houses.

4.2. Vibration and groundborne noise measurements

The presented series of measurements were made in February and March 2011. The measurement setup in each case was decided on the spot after asking the house owners where the noise and vibration problem was perceived as most severe. Strictly speaking this is not quite in accordance with the standard[16], which requires that vibrations be measured where the level is highest. This is usually at a midpoint of the longest span of the structure. In most cases the triaxial vibrations were measured in a room above ground, the groundborne noise was measured in a room underground. Figure 1 shows a typical example of the mounting of the triaxial accelerometer.

***Figure 1.** Rig and the triaxial accelerometer*

4.3. Rail corrugation measurements

Along the line with the most complaints, line 1 Frognerseterlinjen, it was also decided to measure the rail corrugation according to ISO3095-2005[18]. The condition of the rail has been known to be a factor determining the indoor noise and vibrations in nearby dwellings[19, 20, 21]. Accordingly practical tools to measure rail corrugation have been developed[22]. Figure 2 shows the measurements of the rail corrugation. For the other houses, it was not considered necessary to measure the rail corrugation, because the track was in such a poor condition that it was replaced anyway.

Figure 2. *Preparing to measure rail corrugation.*

5. MEASURED RESULTS

5.1. Overview

An overview of the measured results is given in Table 2. The table gives the weighted overall results. A more detailed description of the results from the houses where the rail corrugation was measured follows below together with a more detailed description of the ground conditions.

5.2. Spectra of noise, vibrations and rail corrugation

For six of the houses it's possible to show the spectra of all three parameters together. As the houses are different, a short verbal description of each house is also given. The distance to the metro is given from the house wall to the centerline between the tracks.

5.2.1. House 1-1

This is a modern house where the foundations go down at least 6 meters below ground. It's a semi-detached house. Above ground it's connected with one other house; below ground this chain of two houses is connected with a similar chain of two houses through an underground parking garage. The structural material is concrete below ground, where all the measurements presented have been made. The ground conditions under the track is bedrock just a couple of meters below ground, thus the house it probably built on bedrock.

The measurements of triaxial vibrations were made at a level one floor lower than the metro line. The average measured vibration spectrum is shown in figure 3. The measured level of groundborne noise is shown in figure 4. The results of the rail surface analysis are shown in figure 5.

Table 2. *Overall results.*

House	Distance (m)	V_{w95} x (mm/s)	V_{w95} y (mm/s)	V_{w95} z (mm/s)	L_{AFmax} groundborne (dB)	Rail corrugation
1-1	16	0,07	0,06	0,08	42	Worn rails, broadband corrugation
1-2	16	0,02	0,02	0,12	36	Worn rails, corrugation peak at 12,5 cm
1-3	15	0,03	0,03	0,05	37	Worn rails, corrugation peak at 12,5 cm
1-4	13	0,40	0,29	0,34	37	Worn rails, broadband corrugation
1-5	11	0,05	0,06	0,12	34	Worn rails, corrugation peak at 4 cm
1-6	27	0,02	0,03	0,06	41	Worn rails, broadband corrugation
1-7	10	0,27	0,20	0,40	50	Track replaced - not measured
3-1	70	0,07	0,06	0,08	31	Not measured
4-1	26	0,16	0,13	0,12	30	Track replaced - not measured
4-2	19	0,20	0,08	0,14	42	Track replaced - not measured
4-3	9	0,03	0,03	0,08	38	Track replaced - not measured
6-1	16	0,05	0,06	0,16	39	Not measured

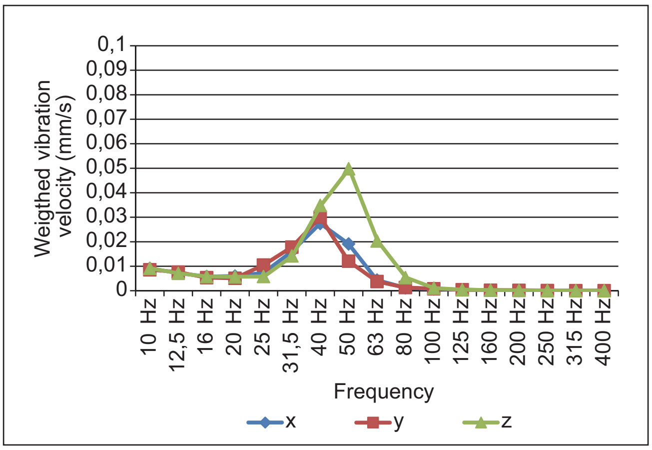

Figure 3. *House 1-1, measured vibrations.*

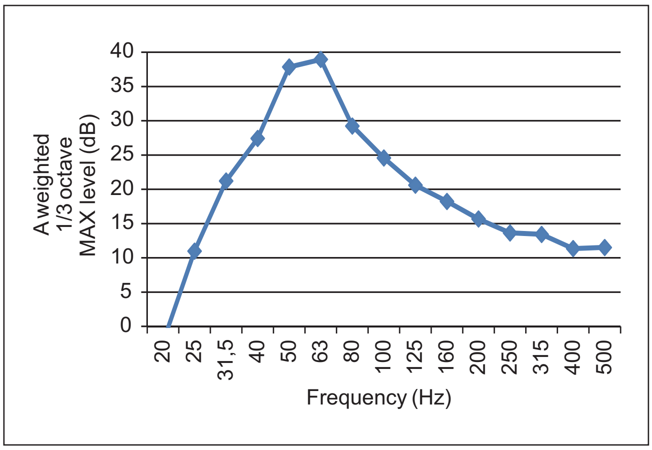

Figure 4. *House 1-1, measured groundborne noise.*

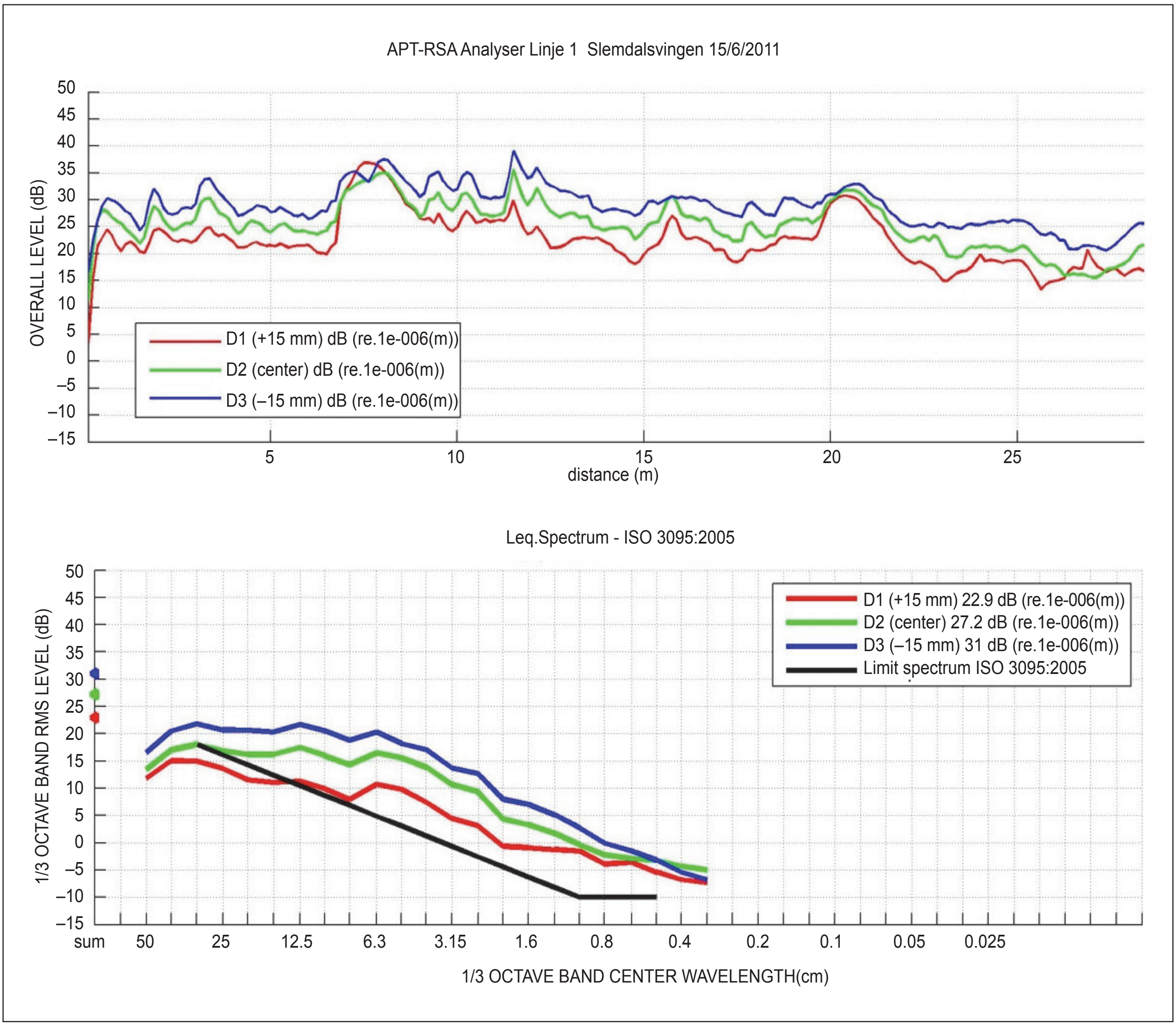

Figure 5. *House 1-1 – rail corrugation.*

The vibrations in the X and Y directions peak at 40 Hz, the vibrations in the Z direction peak at 50 Hz, and the frequency with the highest contribution to the A-weighted level of groundborne noise is 63 Hz. The rail surface analysis gives no indication of a clear pattern of wear on the rails. The trains have different speeds on the different tracks here. For this house, there is not sufficient justification to claim any correlation between rail wear and indoor noise and vibrations.

5.2.2. Houses 1-2 and 1-3

These two houses are neighbors, and the houses are built in the same project. For both houses the structure below ground is concrete, from the ground floor up it's a wooden structure. For both houses the measurements of groundborne noise were made in an underground room with very little airborne contribution to the measured noise. The vibration measurements in house 1-2 were made on the living room floor, which is roughly on the same level as the metro line. The vibration measurements in house 1-3 were made on a bedroom floor roughly 3 meters higher than the metro line. The houses are so close to each other that the rail surface was measured in one go for both houses.

The vibration spectra show different patterns for these two houses. Figure 6 shows the measured vibrations in house 1-2, while figure 7 shows the measured vibration levels in house 1-3. It is reasonable to assume that the different shape of the vibration spectra is due to the different response of the house on the ground floor (house 1-2) and on the first floor (house 1-3).

The groundborne noise spectrum of house 1-2 is shown in figure 8, while the noise spectrum of house 1-3 is shown in figure 9. The shape of the groundborne noise spectra is very similar for these two houses, with a clear peak at 50 Hz.

The rail surface analysis shows a clear pattern of a repetitive wear on the rails. The speed of all the trains

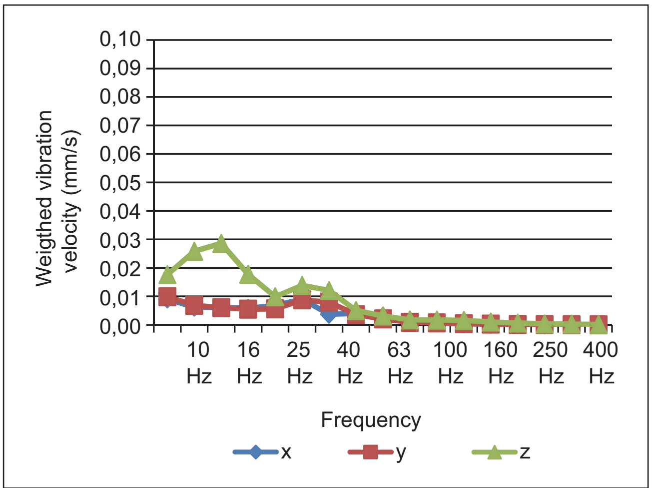

Figure 6. *Vibrations in house 1-2.*

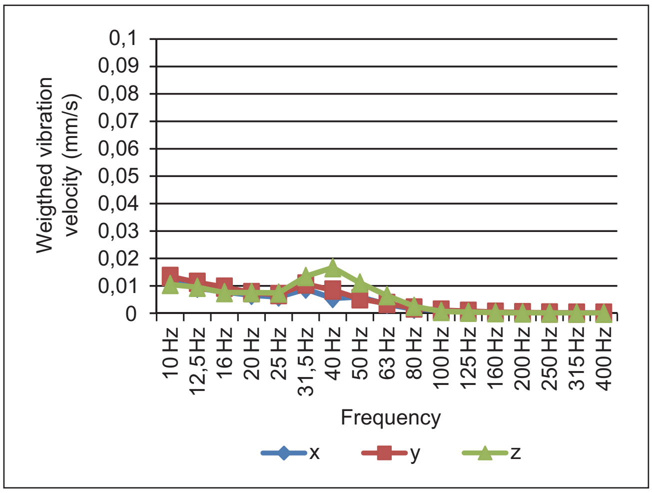

Figure 7. *Vibrations in house 1-3.*

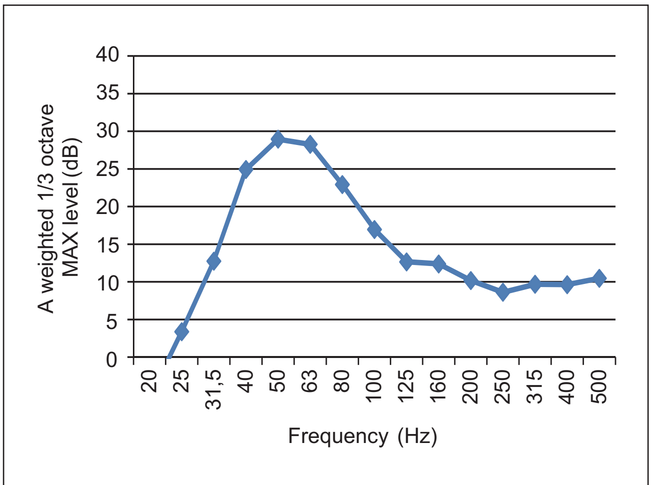

Figure 8. *Groundborne noise in house 1-2.*

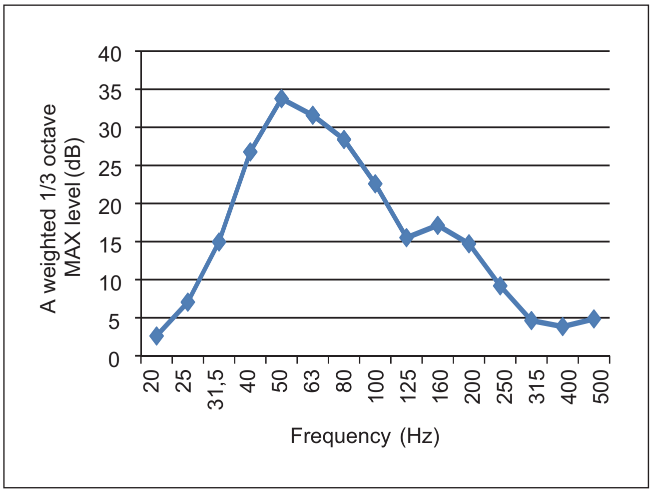

Figure 9. *Groundborne noise in house 1-3.*

passing by was in the range 6-7 m/s. The rail surface analysis shows a peak at 12,5 cm wavelength. This could correspond to a frequency in the range of 50 Hz. The results of this measurement are shown in figure 10.

The match between the critical frequencies of groundborne noise is good, the 50 Hz peak is still there when A-weighted. For the vibrations it is more difficult to find any connection.

The ground conditions under the track close to these houses seem to be thick layers of firm clay.

5.2.3. House 1-4

This house is close to the metro line. It has a concrete substructure, and the floor of the 1st floor is a concrete slab. The walls above ground are wooden structures. The vibration levels are measured on the kitchen floor. This floor is roughly on the same level as the metro line. The groundborne noise is measured on a bedroom at a level about 3 meters lower than the metro line. For this house, there is a pronounced difference in vibrations depending on the direction of the trains. The inbound trains towards the city centre are closest to the house, and they give rise to substantially higher vibration levels. The measured vibration levels for this house are the highest measured in this report. The vibration was clearly feelable during the passage of the metro trains, and the groundborne noise was definitely uncomfortable during the passages. The measured vibration levels on the kitchen floor are shown in figure 11, while the measured groundborne noise is shown in figure 12.

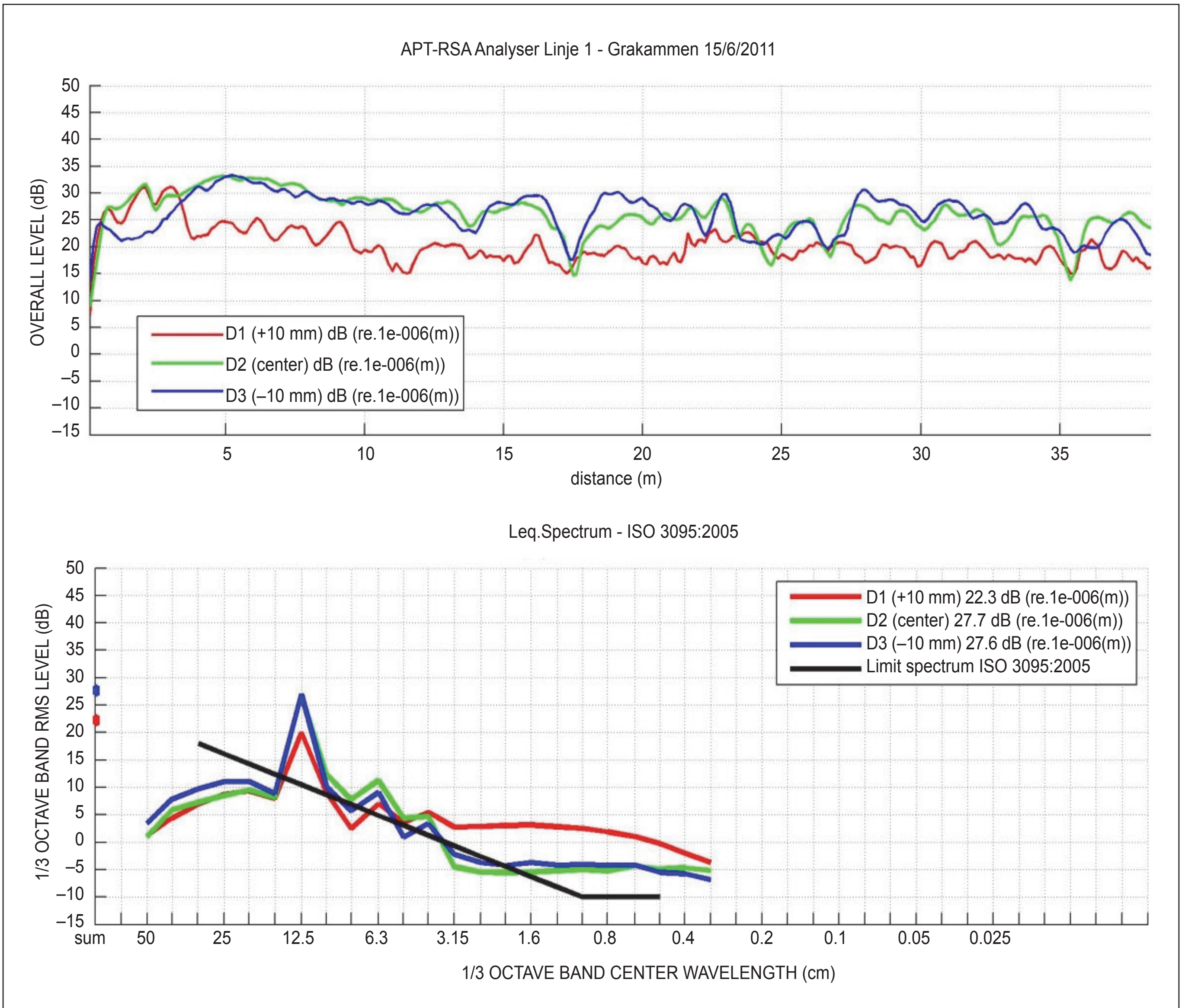

Figure 10. *Rail surface analysis for house 1-2 and 1-3.*

The rail surface analysis shows the rails are clearly worn, well above the limit spectrum given in ISO 3095:2005. But there are no clear peaks in the rail surface analysis. The results of the measurement are shown in figure 13. For this house the trains in both directions were running at speeds of 25 – 30 km/h, which might correspond to frequencies in the range 17 Hz to 33 Hz when the train runs on a rail with

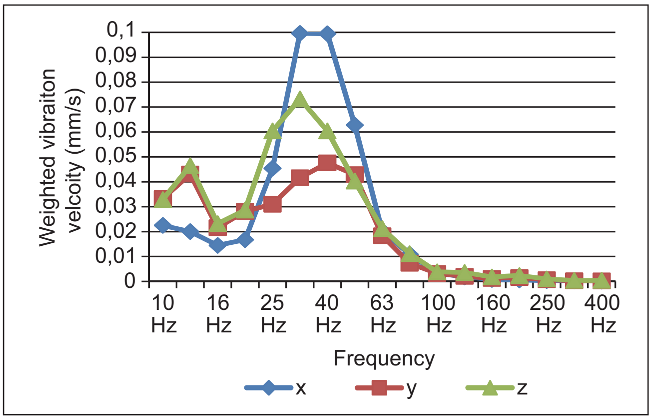

Figure 11. Vibrations in house 1-4.

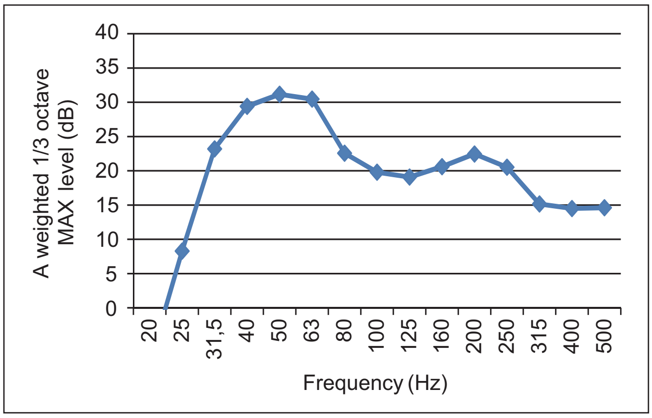

Figure 12. Groundborne noise in house 1-4.

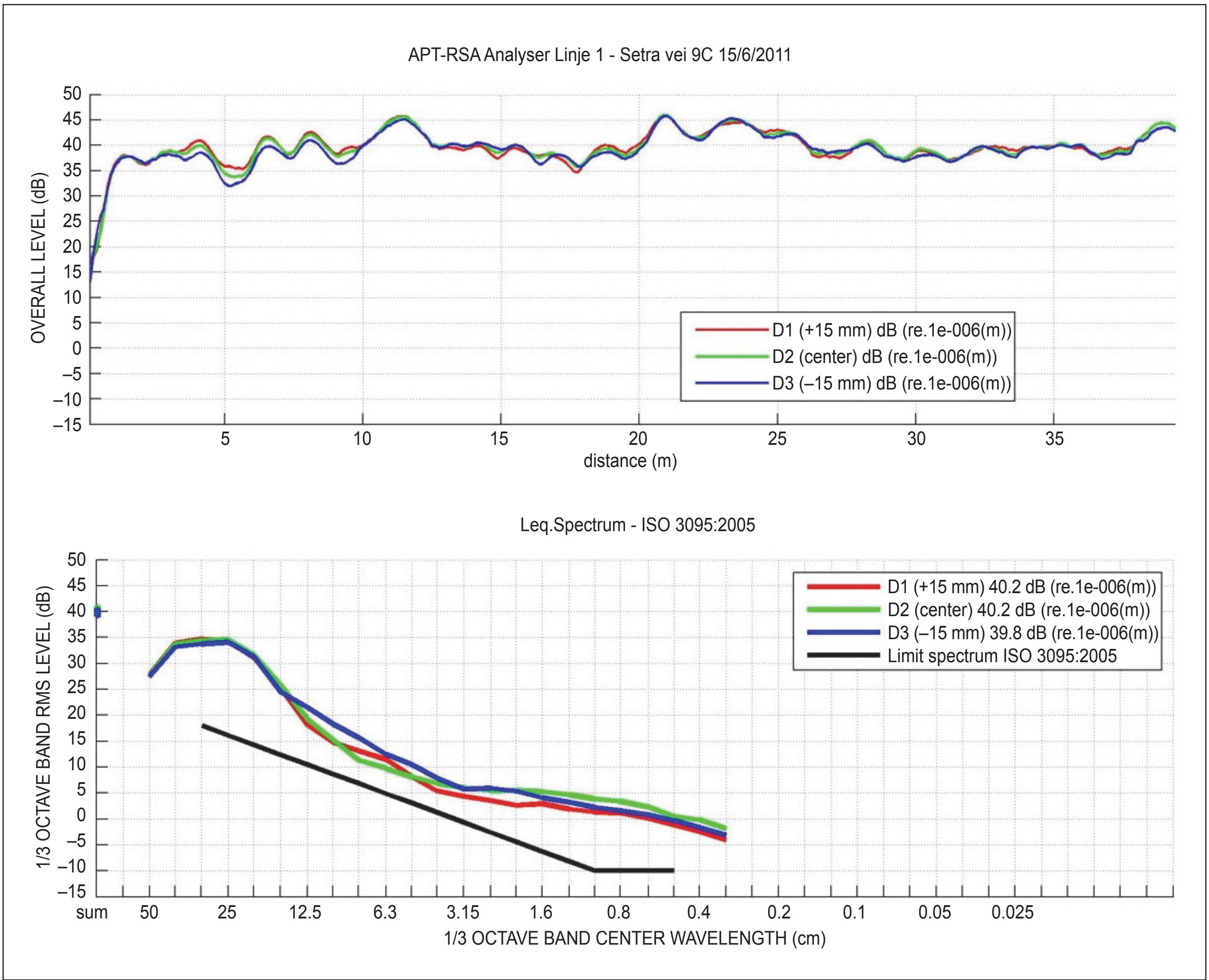

Figure 13. Rail surface analysis for house 1-4.

corrugation wavelengths of 25 to 40 cm. This is a reasonable but not perfect match between the peak frequencies for rail corrugation, vibrations and groundborne noise.

The ground conditions under the track for this house seem to be firm clay down to bedrock 5-10 meters below the track.

5.2.4. Houses 1-5

The house is close to the metro line. The structure below ground is concrete, above ground it's a wooden structure. The vibration levels are measured on a kitchen on the ground floor. This floor is on roughly the same level as the metro line. The measurements of groundborne noise were made in a bedroom on the same level without windows facing the metro line. Interestingly the vibrations show peaks at different frequencies in different directions. The measured vibration levels are shown in figure 14, while the measured groundborne noise levels are shown in figure 15.

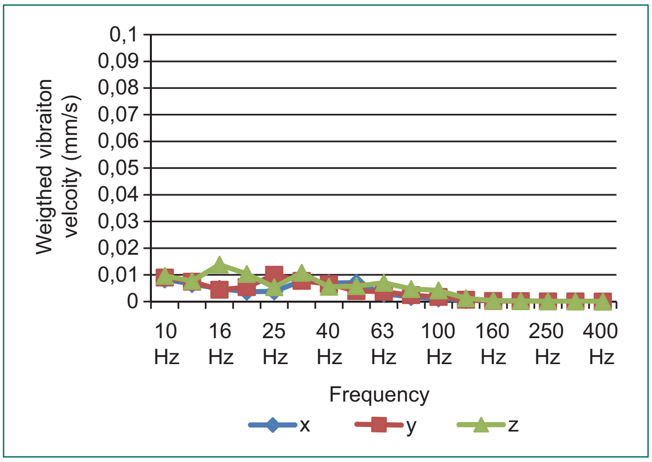

Figure 14. *Vibrations in house 1-5.*

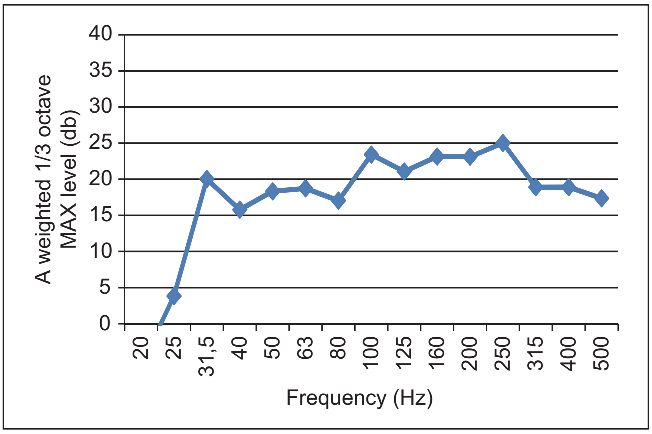

Figure 15. *Groundborne noise in house 1-5.*

A detail picture of the rail past these houses is shown in figure 16, while figure 17 shows another view of the rail. The rail surface analysis shows a clear peak at 4 cm wavelength. In addition the rails are generally worn. The results of the measurement are shown in figure 18. There is no clear peak in the spectra of the groundborne noise and vibrations. There is however a small top in the noise of groundborne noise at 250 Hz, which could fit in with the rail corrugation measurements.

Figure 16. *Detail of rail*

Figure 17. *Averview of rail*

The ground conditions under the track for this house seem to be firm clay down to bedrock 5-10 meters below the track.

5.2.5. Houses 1-6

This house lies higher than the metro line. The vibration measurements are made on the ground floor in a living room. The vibration levels are distributed over a wider frequency range than for most of the houses. The vibration levels are shown in figure 19, while the groundborne noise levels are shown in figure 20. The rail surface analysis, figure 21, shows that the rails are generally worn past this house without any clear peak.

The ground conditions on the track itself are as follows: Firm clay down to about 5 meters below the track, where bedrock was found. It is quite likely that the house rests on firm clay and/or bedrock.

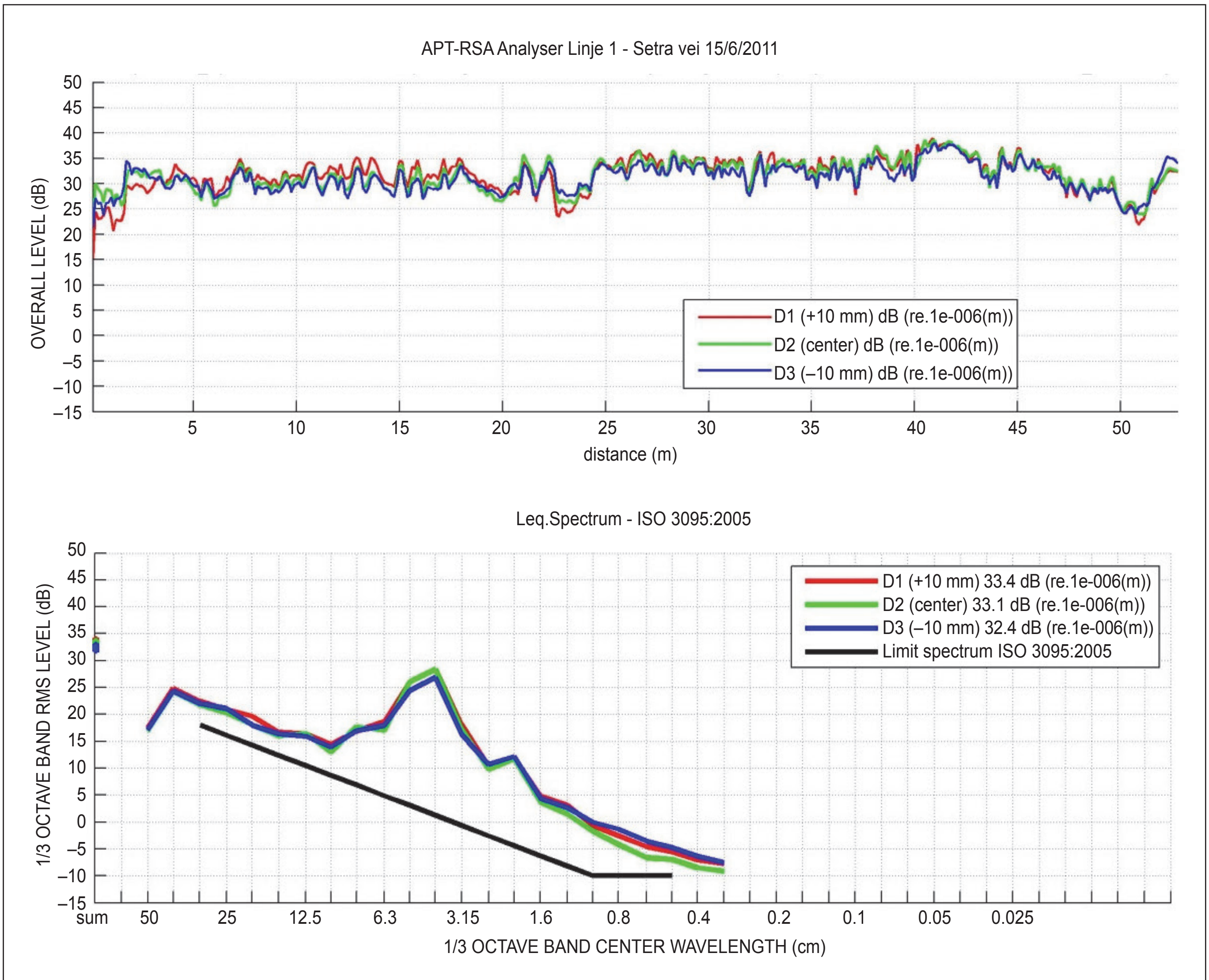

Figure 18. *Rail surface analysis for house 1-5.*

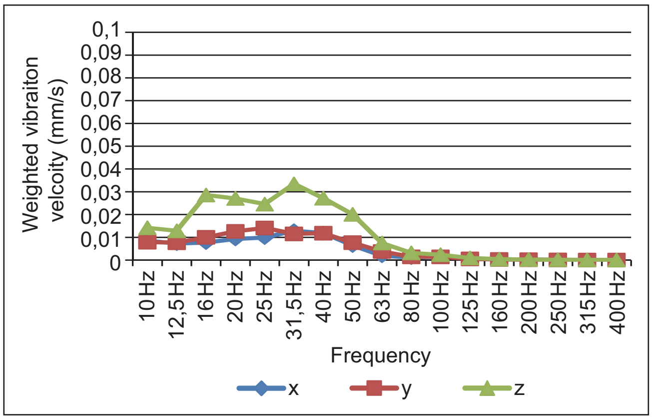

Figure 19. *House 1-6, vibrations.*

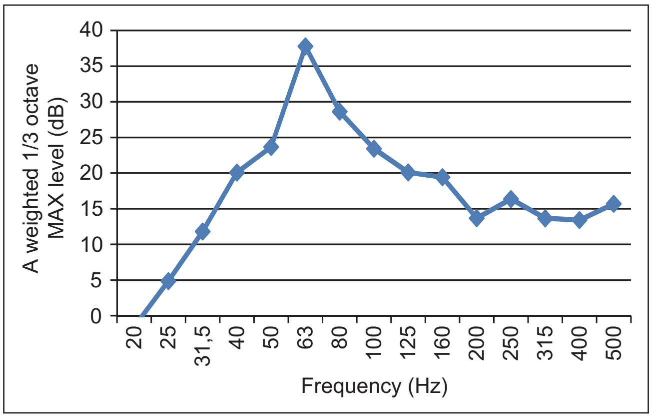

Figure 20. *House 1-6, groundborne noise.*

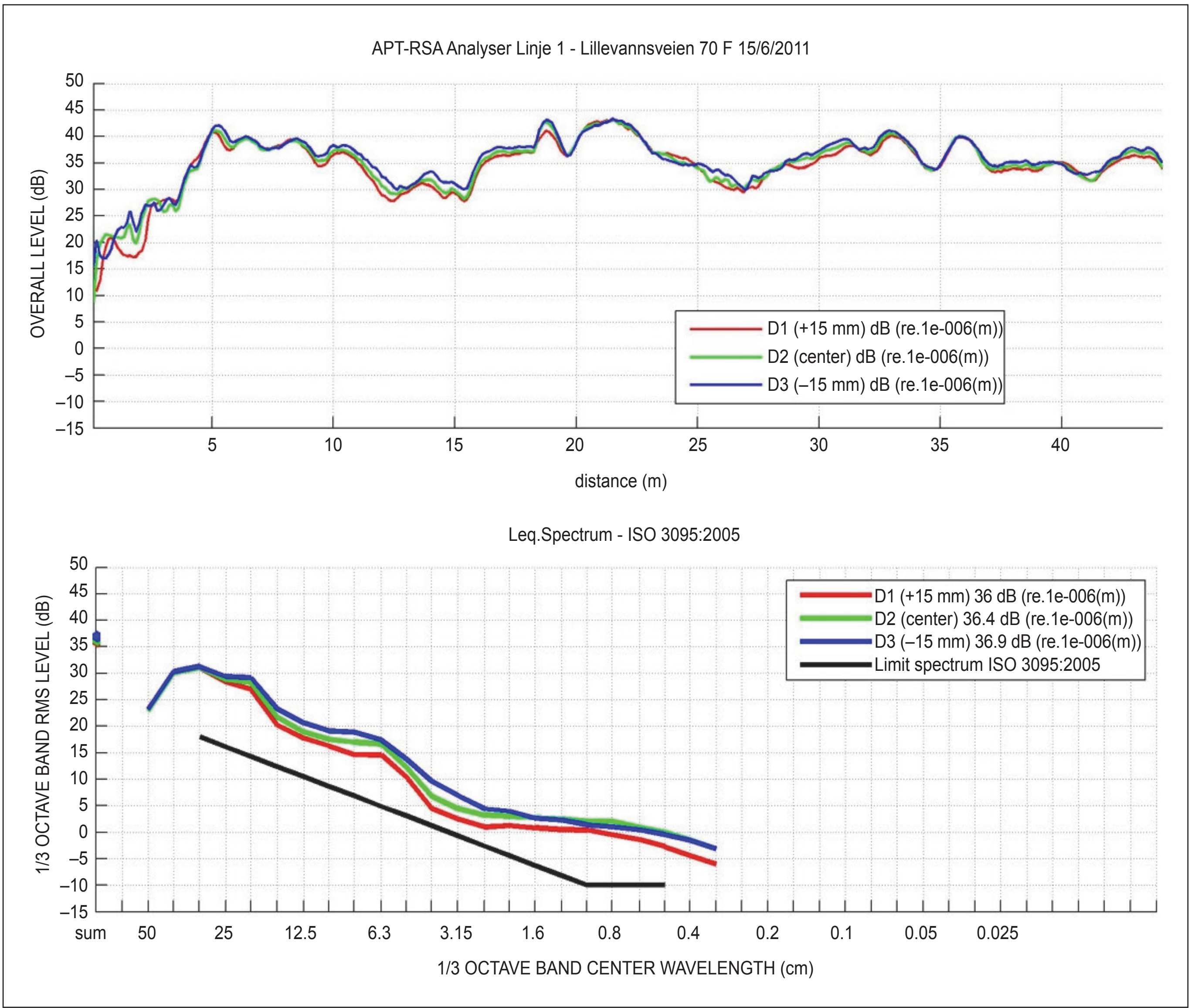

Figure 21. *House 1-6, rail surface analysis.*

6. COMMENTS

Measurements of vibrations and groundborne noise from Oslo's metro have been presented. This article should be viewed as a pilot report from an ongoing project to learn about the sources and transmission paths of vibrations into houses. The measurements of rail surface corrugation show that the rails are worn, in some cases in a repetitive pattern. For the houses 1-2 and 1-3 there is a reasonable match between the spectra of the rail corrugation and the groundborne noise, but not for vibrations. In house 1-4 there is a reasonable match between the peak frequencies of rail corrugation, groundborne noise and floor vibrations. For house 1-5 there is some indication of a higher noise contribution at a frequency compatible with the rail corrugation measurements.

7. CONCLUSIONS

The A-weighted spectra of groundborne noise are similar in shape for all the houses. The vibration spectra do not show a consistent pattern. More data are needed, particularly regarding transfer functions between the ground, the building foundation and the floors in the rooms. It is likely that worn rails cause increased noise and vibrations in houses along the metro lines. In four of the houses where measurements have been made, the connection is indicated by the measurement results.

8. FURTHER RESEARCH

The presented measurements of vibrations, noise and rail surface do not point out a clear correlation. There is a need for a larger series of measurements in other houses.

8.1. Transfer functions from ground to house

Japanese research has shown well behaved transfer functions between vibrations in the ground[8], vibrations on the building foundations and vibrations on the floors of residences. This even applied to houses exposed to vibrations from different types of sources of vibration. It would be very interesting to measure such transfer functions on Norwegian houses. Initial measurements indicate that the transfer functions may be less predictable than in Japanese houses[23]. This may be due to Japanese houses being earthquake resistant and more uniformly built than Norwegian houses. Future measurements will include transfer functions.

8.2. Transfer of vibrations from trains to the ground

The transfer of vibrations from the metro train via the track into the surrounding ground is not well known. It is very likely that the construction of the boggies, the wheels and the track may all be critical. Another factor to be considered is that the metro trains are usually only a source of vibration at short distances. The whole area between the track and the house may actually be within the near field. This requires further research.

8.3. Seasonal variations

All the residence owners that have been visited during these measurements have claimed that the vibration levels vary significantly between winter and summer. In particular many of the house owners claim increased vibration levels during especially cold periods. It is quite possible that this is correct, as it is quite conceivable that the mechanical properties of the soil change with the seasons. It could be investigated using long-term measurements of vibrations in one point.

ACKNOWLEDGEMENTS

Our sincere thanks go to Oslo region transport engineering section (Kollektivtransportproduksjon, the publicly owned company that runs Oslo's metros and trams). This company has commissioned the measurements and allowed the publication of the results. In addition we would like to thank Lars Fredrik Nordin of Brekke & Strand akustikk for proofreading the manuscript and several suggestions for improvement to the text.

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Relevance of the bass sounds for acoustic comfort and noise control in rooms

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PACS CODE: 43.55.Br

ABSTRACT

Measured frequency spectra in music and speech indicate relatively strong energy contents below 250 Hz. In smaller spaces these inevitably excite room resonances. These can cause detrimental masking effects on the higher frequency sounds, which carry the bulk of useful information. The reverberance characteristic of an enclosure is identified as a decisive parameter for the clarity of music and the intelligibility of speech. Two representative examples are to demonstrate its relevance for the acoustic quality of and noise control in spaces of different size and use. Broadband absorption thus becomes an indispensable necessity in the design and planning for contemporary architecture and retrofit measures in restoration projects. This issue which is currently still a minority view among acoustic consultants calls for a thorough discussion in a journal devoted to acoustics in practice.

1. INTRODUCTION

Standard room acoustic design concepts aimed at sound quality and/or primarily noise control in small, as well as in large spaces, normally focus on the medium frequencies (mf) between 500 Hz and 1000 Hz or 2000 Hz. At the equally relevant low frequencies (lf) between 250 Hz and 63 Hz or below, acoustics are characterized by wave interference effects in non-diffusive sound fields. These may influence not only the reception and transmission of sound, but also its emission from lingual and musical sources.

In a technical committee asked to revise the German standard DIN 18041 under the new title “Acoustic quality in rooms —specifications and instructions for planning” the author was confronted with a massive majority opinion denying a noteworthy practical relevance of acoustical effects far below 500 Hz or 250 Hz. In view of the extraordinary ergonomic and economic importance of this issue he therefore wants to present some evidence for his own contrary conviction and practical experience as a researcher, inventor, lay musician and consultant in this field. Pains were taken to underpin his minority views by referring to fundamental investigations into and publications on this controversial topic with a considerable practical impact— a very suitable case to be treated and disputed in an open access journal. In subsequent papers it is intended to elaborate the lf problems and present a number of representative case studies showing how to cope with an omnipresent acoustical problem in a variety of high-demand smaller and larger spaces for different uses.

2. CHARACTERISTIC FREQUENCY SPECTRA IN MUSIC

In qualifying rooms acoustically it is common practice to consider more the mf range between 500 Hz and 1000 Hz or 2000 Hz and less to the lower frequencies in the wide acoustical cosmos as defined on Figure 1 in accordance with standard textbooks [1]. Following an experienced tonmeister [2], however, the range from 16 Hz to 250 Hz has singular significance: it is well knowing that from 63 Hz downward an audio-correct performance and reproduction becomes progressively more difficult. In these five octaves, the foundation of all coherent sounds manifests itself, including those transition processes and background noises of the natural musical instruments and singing voices that contribute substantially to the sound experience. While pure hearing is accompanied by biomechanical vibrations in the human body below 100 Hz, tones at 50 Hz and below can develop a saturated, enveloping, sonorous overall impression if the room does not ruin this experience from the start with own, always very unharmonious resonances.

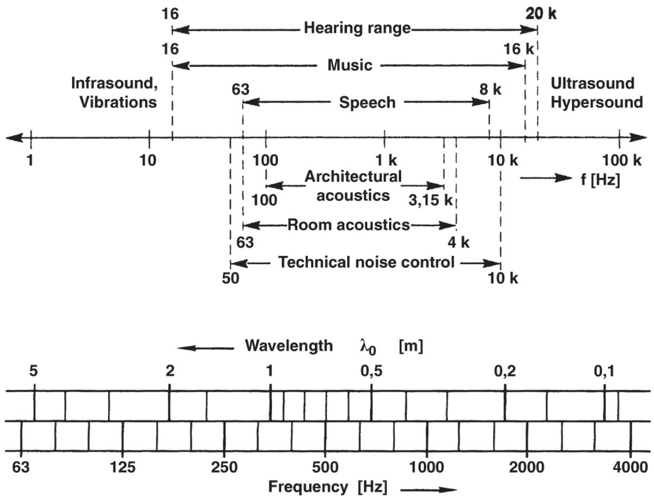

Figure 1. Relevant frequency ranges for practical acoustic tasks (top) and corresponding wavelengths (bottom) after [1].

At 16 Hz usually lies the lowest noted tone, the sub-contra C of the longest (and rare) organ pipe. Of the other musical instruments only the contra-bass, contra-fagot, bass-tuba, harp, grand piano and big drums with their varyingly strong fundamental tones reach down to the contra octave. Less well known and regarded is, however, that all wind and string instruments, especially the pluck and percussion instruments such as harp, piano, drums, timpani, tuba, bongo, gong, xylophone, marimba, vibraphone do not only emit their musically defined tones, but when starting to strike, blow, bow or changing the pitch, reversing bowing, vibrato, etc. also emit in addition aperiodic, under circumstances, quite broadband sounds.

Figure 2 shows, as an example of the temporal evolution of the sound spectrum in the near field, thus without strong room influence, of a grand piano upon striking a single key. Apart from the fundamental tone at 1,047 Hz, which upon looking, respectively listening, closely develops gradually (after about 50 ms) from a noise-like spectrum, some, partly only weakly developed, harmonic tones at about 2,094 Hz, 3,141 Hz and 4,188 Hz can also be detected. Below the fundamental, equally long resounding components are detectable down to very low frequencies. which although weakly perceivable due to the specific sensitivity of the human ear, may greatly interfere at some distance from the source with reflections from the room´s boundaries and thus can influence the listener's hearing impression which always wants to concentrate on a distinct direct sound field of the source(s). Hence excitation of individual resonances of small rooms as treated in [4] and interference effects in large rooms as discussed in [5] can have a very strong negative effect on the desired cultivated lf reception.

When different tones are blown on a clarinet, relatively energetic sound components occur below 125 Hz (Figure 3). How good musicians are able to intentionally influence these sub-tones artistically can be seen, for example, in Figure 4 analyzing a string *pizzicato.* Plucked without vibrato, at 247 Hz the fundamental tone sounds much longer than its harmonics. However, with *vibrato* a large part of the vibration energy feeds the low tones, which then resound longer than the other partial tones as long as the vibrating pressure of the left finger on the respective string holds.

Of course, harmonic and intermediate tones, noises and lf sub-tones develop particularly diversely with percussion instruments. Figure 5 shows, for example, the evolution of the sound spectrum of the timpani tuned to A, corresponding to 110 Hz: the intermediate tones, e.g. the first ring mode, do not decay until after 0.5 s; the sub-tones remain strong beside the principal mode, the fifth and octave even after 1 s.

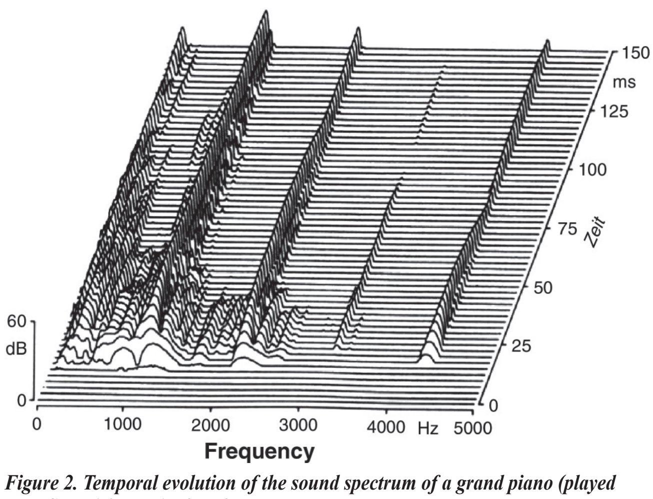

Figure 2. Temporal evolution of the sound spectrum of a grand piano (played note $C_6 \rightarrow$ 1,047 Hz) after [3].

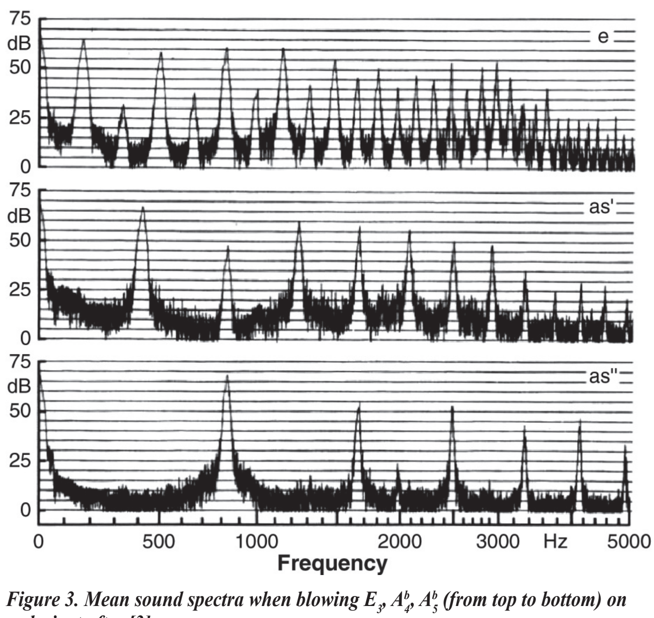

Figure 3. Mean sound spectra when blowing E_3, A^b_4, A^b_5 (from top to bottom) on a clarinet after [3].

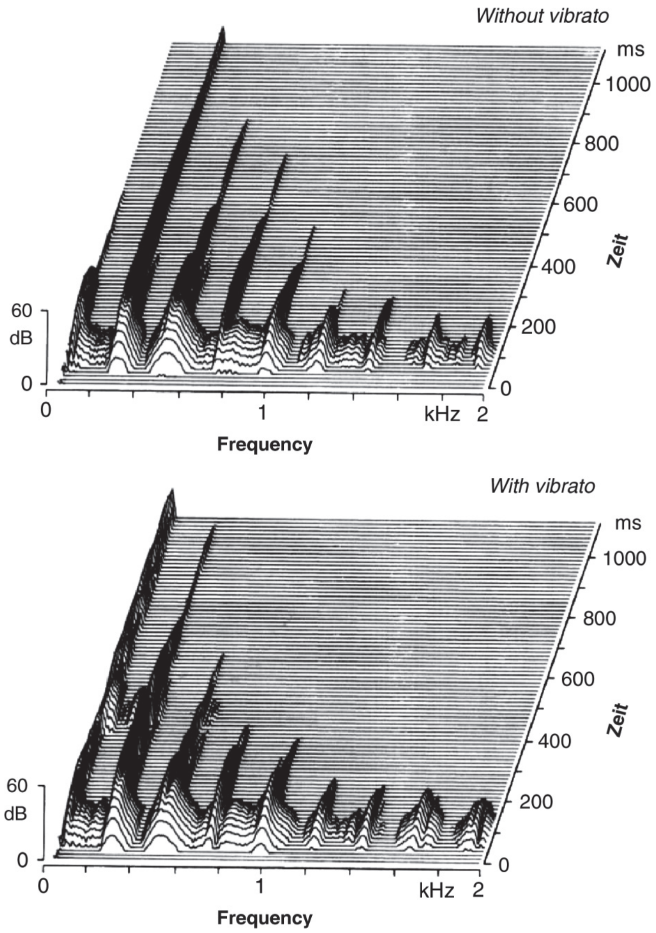

Figure 4. Evolution of the sound spectrum when plucking B_3 on a violin without (top), resp. with vibrato (bottom) after [3].

3. CHARACTERISTIC FREQUENCY SPECTRA IN SPEECH

When looking at the sound which is self-generated by users communicating in a room, its A-weighted spectrum typically exhibits a broad maximum between 500 Hz and 2000 Hz and a steep descent towards 63 Hz. Figure 7 shows the results obtained in the waiting area of a Chinese hospital on a relatively quiet afternoon with about 10 people awaiting an ultrasonic diagnosis. The standard deviation of the SPL measured in octave bands at 9 different locations was just below 1 dB. This may indicate that the room was acoustically well treated. A look at the un-weighted spectrum proves that the lf sound nevertheless takes a considerable portion of the total sound energy with its maximum at 500 Hz and 250 Hz and a moderate decay towards 125 and 63 Hz. This agrees with the evaluation in [7] yielding a difference of, after all, +3.5 dB between C- and A-weighted SPL, even a bit more than predictable from the findings in [8] for a speech level of just above 60 dB(A), see Figure 8. For slightly higher levels around 68 dB(A) of 5 radio announcers all the frequency distribution curves in Figure 9 exhibit a maximum at as low as 250 Hz, again most likely recorded under highly absorbent studio conditions, i.e. without strong lf amplification by room modes.

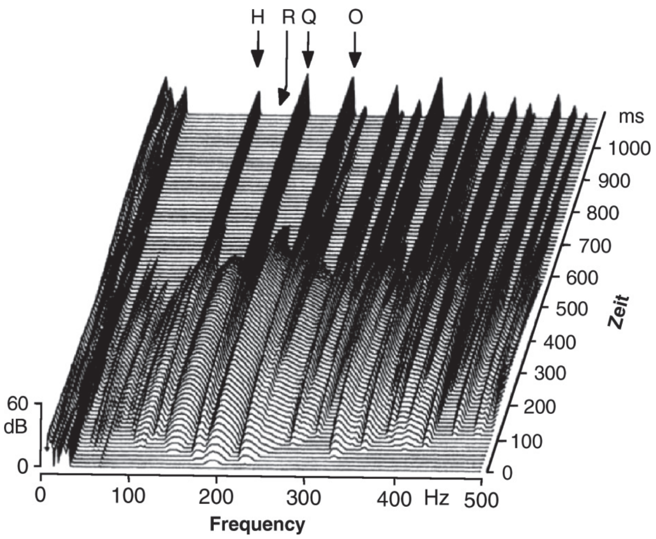

Figure 5. Time evolution of a timpani spectrum of pitch A after [3]; P Principal mode, R 1st Ring mode, F Fifth, O Octave.

The "visible speech" example on Figure 10 exhibiting the sentence "Wissen kann man sich nicht erkaufen",

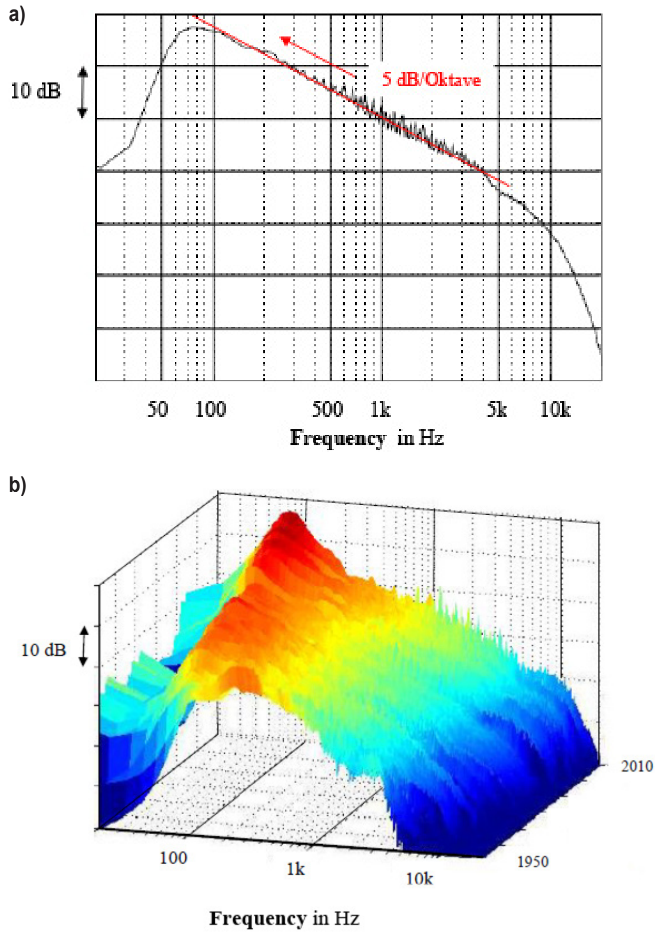

Figure 6. Averaged spectra of 772 recordings of popular songs exhibit a clear lf energy maximum, which has continuously shifted from about 200 Hz in the fifties below 100 Hz in 2010 according to [6].

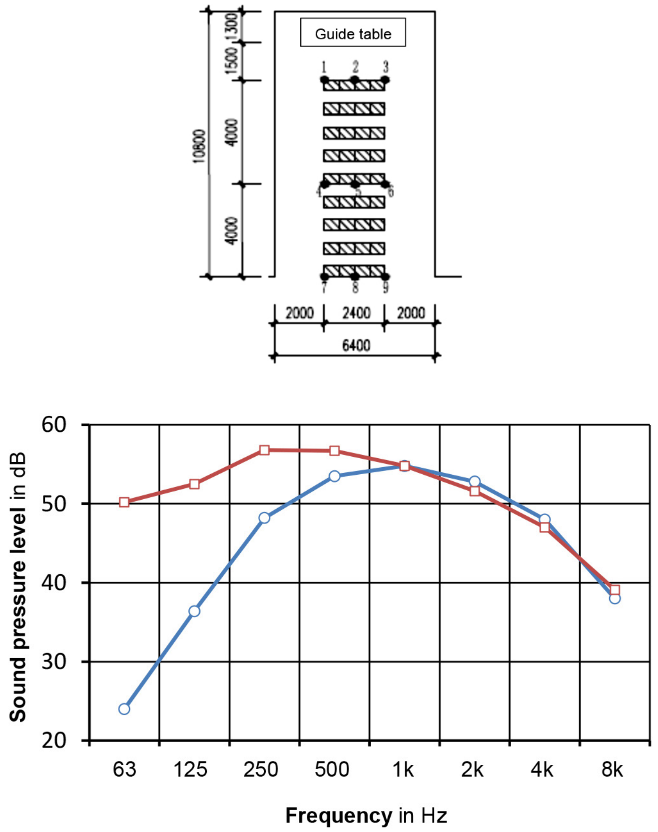

Figure 7. Noise spectra created by 10 patients awaiting treatment in the waiting room of a Chinese hospital [7]; un-weighted (□) respectively A-weighted octave levels (○) averaged over 9 locations.

taken again from a comprehensive textbook on the acoustical foundations of speech communication [9], also visualizes strong lf energy whenever the SPL (upper graph) of the speaker peaks.

Most of these speech sound analyses may have been performed under more or less anechoic room conditions. The detrimental effects which the "booming" modes of an untreated room may have becomes also obvious when looking at the phoneme-group octave-band

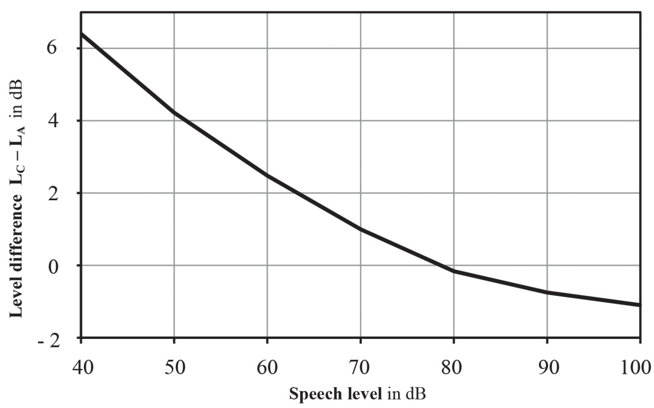

Figure 8. Level differences $L_C - L_A$ indicating a considerable lf frequency content depending on a varying speech level as averaged over 100 persons according to [8].

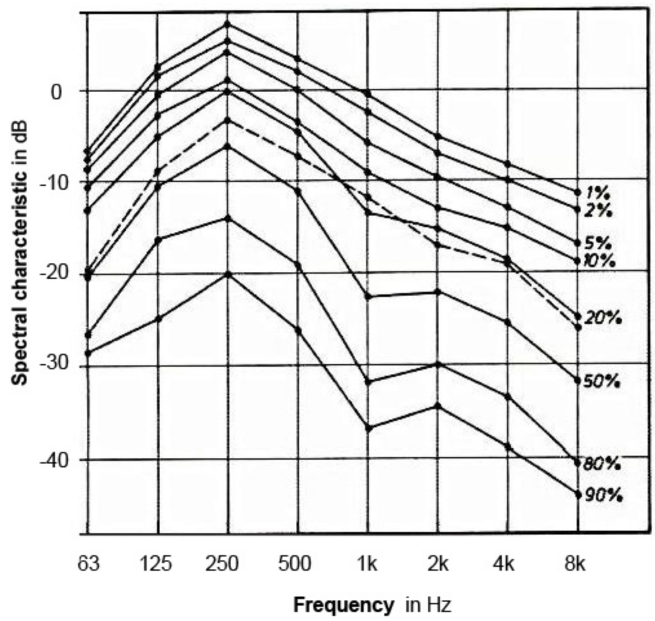

Figure 9. Frequency distribution of sound spectra created by 5 radio announcers as relative to a SPL of 68 dB(A) averaged over 5 minutes after [9].

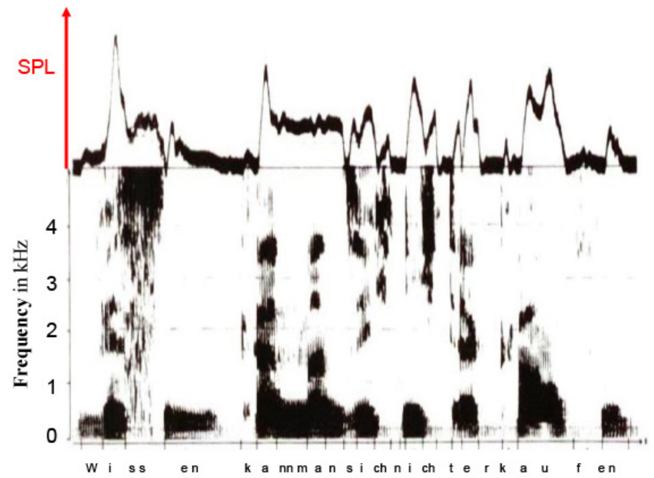

Figure 10. "Visible speech" for the sentence "Wissen kann man sich nicht erkaufen" after [9].

weights in predicting speech intelligibility according to [9]. These show a continuous increase from 1000 Hz to 125 Hz in single fricative and explosive as well as in the averaged phoneme spectra (Figure 11). Unfortunately, as in so many psychoacoustics and room acoustics investigations, it is common practice to neglect what could be measured below 125 Hz. It is, however, extremely unlikely that the spectra in Figure 11 would fall much in the 63-Hz octave, certainly not below that in the kHz range.

While normally less attention is paid to the lf content in a noise spectrum due to the much lower sensitivity of the human ear at these frequencies, the corresponding lf sound energy may nevertheless provoke a strong

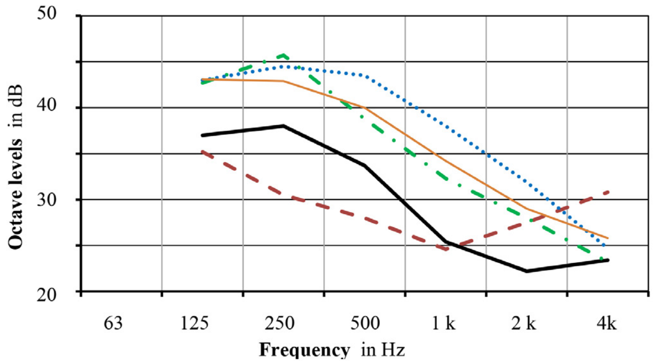

Figure 11. Octave spectra of fricative (dashed), explosive (thick), semi-vocal (dash-dotted), vocal (dotted lines), and averaged over 10 male speakers; all showing strong lf energy levels according to [10].

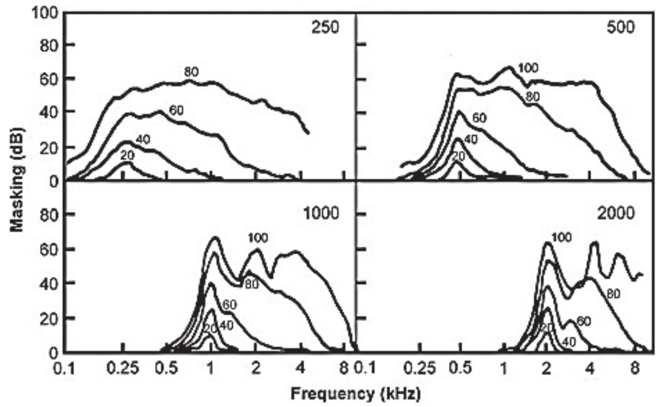

Figure 12. The higher the lf noise level (between 20 and 80 dB at frequencies between 250 Hz and 2000 Hz as shown), the more it shifts the hearing threshold for the relevant hf sound according to [16].

response of the room as well as of the biomechanical vibration of the human body and of the human mind. More information about the lf content in speech may also be gathered from a wealth of analyses undertaken by *K. Genuit* and his colleagues at HEAD acoustics GmbH in their continuing efforts to prove how really inadequate single-number noise ratings are when these are merely based on A-weighted parameters of any type of sound exposure [11, 12].

4. MASKING OF HIGH- BY LOW-FREQUENCY SOUNDS

Once the very broadband nature of the sounds in music and speech events has been realized, one immediately hits upon their mutual interactions in real situations. It is known, of course, that the bulk of any acoustical information is normally contained in the lower-energy hf regime in the kHz range. That does, however, not mean that one may forget about the high-energy lf part of source spectra as noted in sections 2 and 3. When the latter gets a chance to excite a strong room response one may easily imagine how this phenomenon causes dramatic effects on the hf part of the spectrum, which is considered as particularly relevant for the clarity of music and intelligibility of speech.

In smaller spaces the lf energy inevitably excites the individual room resonances ("modes") as discussed e.g. in [13, Chap.2], which can only be controlled by suitable broadband absorbers as described e.g. in [14] and [15]. If these are allowed to boom unimpededly, the clarity of music and the intelligibility of speech are far too often hampered by masking effects on the hf part of the spectrum, see e.g. the series of "masking audiograms" in Figure 12. Each panel shows the amount of masking (shift in hearing threshold) produced by a given pure tone masker presented at different intensities [16]. The masking does, most likely, also remain strong from disturbances due to background noises or room modes in the lower octaves 125 Hz and 63 Hz, see also [10, Sect. 11.3], although again it is common practice to overlook this fundamental part of the spectrum.

5. REVERBERANCE AND ACOUSTIC QUALITY OF SPACES

A large number of contemporary concert and assembly halls are criticized for their mediocre acoustics although most elaborate model tests and computer simulations are at our disposal for the large-scale planning and small-scale interior design of an enclosure. On the other hand, we have inherited numerous spaces with excellent acoustics which were built without any powerful prediction and calculation tools. Acousticians or sound engineers may complain that nowadays "*architects almost exclusively consider the visual aspects of a structure. Only rarely do they consider the acoustic aspects*" [17]. But are we able to provide the builders with a firm and practicable guideline for achieving acoustical quality and comfort in a room for a specific musical or lingual destination?

As an acoustician one may retreat to the recently released standards ISO 3382-1 and 3382-2 which "*continue to specify room acoustic quality by reverberation time (T in s) alone*" for performance spaces and ordinary rooms. These standards concentrate on the measurement of:

$$T(f) = 0.16\frac{V}{A(f)}, \qquad (1)$$

where V is the room volume in m^3 and both T and the equivalent absorption surface A in the room are strongly frequency dependent in the relevant range between (at least) f = 63 Hz and 8000 Hz for room acoustics in general. The standards consider a restricted range between, after all, 100 Hz and 5000 Hz as sufficient for a "*fundamental description of the* *acoustical character of an auditorium*". Strangely enough, however, they seem to take this range of T(f) as merely "*related to the physical properties of the auditorium*". When, in (only informative) Appendix A, several quantities are introduced which are meant to be "*correlated with particular subjective aspects of the acoustical character of an auditorium*", e.g. early decay time EDT, strength G, clarity C_{80}, definition C_{50}, and center time T_S, the focus is only on a much more restricted mid frequency (mf) spectrum between 500 and 1000 Hz (also for the single-number ratings which prevail in practice in summarizing measurements). As a result, one rarely finds acoustics criteria for the complete frequency spectrum. Instead, standard recommendations usually just refer to a correspondingly averaged T_m as a function of room volume.

Figure 13 from DIN 18041-2004 e.g. shows T_m recommendations for different uses. A certain increase with total volume only reflects the general experience and expectation that larger rooms resonate longer than smaller rooms due to correspondingly extended free wave paths between reflections from absorbing boundaries. The magnitude of T_m which should be recommended, or could even be made compulsory for an individual enclosure, is far less clear.

As a prominent example with a T_m value far beyond that suggested according to Figure 13, the Jesus-Christus-Kirche in Berlin-Dahlem was discussed e.g. in [5] and documented in more detail in [13, Sect. 11.12]. The space was built in 1931 and became world-famous after the war as a performing and even more as a recording space for countless symphony orchestras, music ensembles, choirs and soloists, who to date are without exception enthusiastic about its outstanding acoustical qualities. This venue (Figure 14), after only minor reconstructions, now has a volume of roughly 8000 m^3. Figure 13 and international standards would require a T_m between 1.8 and 2 s for music and 1.3 to 1.5 s for speech.

Accordingly feared and vehemently argued during the design phase by the acoustic consultant in charge, a much higher reverberation was (luckily!) achieved instead. It is decisive, however, as the measurements, which were taken years later, document (Figure 15) that the spectra remarkably drop from relatively high values around 2.6 s at 1000 Hz to relatively low 1.3 s at 63 Hz yielding a bass ratio

$$BR = \frac{T_{125} + T_{250}}{T_{500} + T_{1000}} \qquad (2)$$

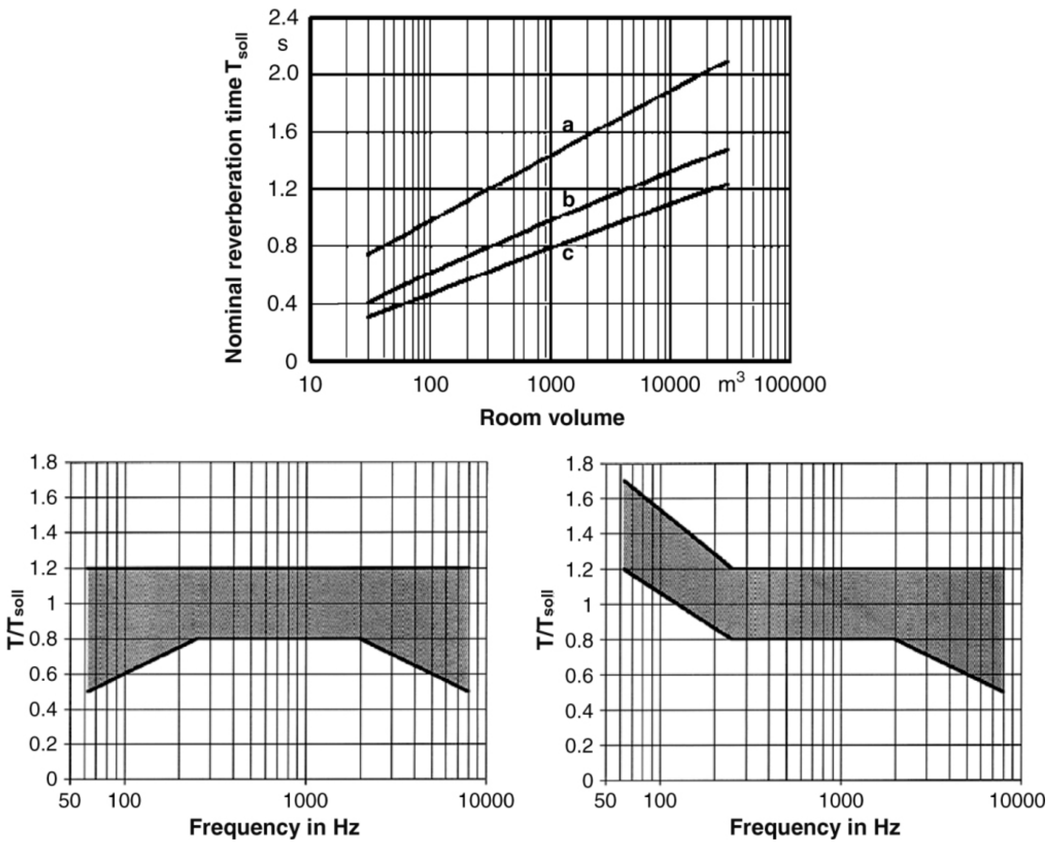

Figure 13. *Recommended mean reverberation time T_{soll} (averaged between 500 Hz and 1000 Hz) in occupied rooms; for musical presentation (a), speech presentation (b), communication and teaching (c) as a function of room volume V (top) and tolerance range T/T_{soll}, as a function of frequency for speech (bottom left) and music (right) according to DIN 18041-2004.*

Figure 14. *View of the nave in the Jesus-Christus-Kirche in Berlin-Dahlem [2, 11].*

as small as 0.67. This is definitely far below what is generally recommended for any music (1.1 for a generally high, respectively 1.5 for low reverberance).

This specific reverberance resembles that in numerous baroque churches and has become a model for many other buildings which will become sample subjects in a companion paper in this journal.

6. REVERBERANCE AND NOISE CONTROL IN ROOMS

Noise control, particularly in smaller rooms, has to cope with a specific problem in the range below what is usually defined as *Schröder* frequency

$$f_S = const\sqrt{\frac{T}{V}} \tag{3}$$

in Hz, a simple derivative from volume V in m^3 and reverberation time T in s respectively damping in the room. The constant is estimated as 1200 in [18], 2000 in [19] and, even more realistically, 4000 in [20]. For typical classrooms or medium-sized rehearsal spaces with V ≈ 200 m^3 and an almost optimal T = 0.8 s any sound field emitted may be affected below f_S ≈ 76 – 252 Hz by a limited number of discrete room resonances, see e.g. [13, Chap. 2]. A less optimal T = 1.4 s would shift f_S to values between 100 Hz and 335 Hz, i.e. in any case well

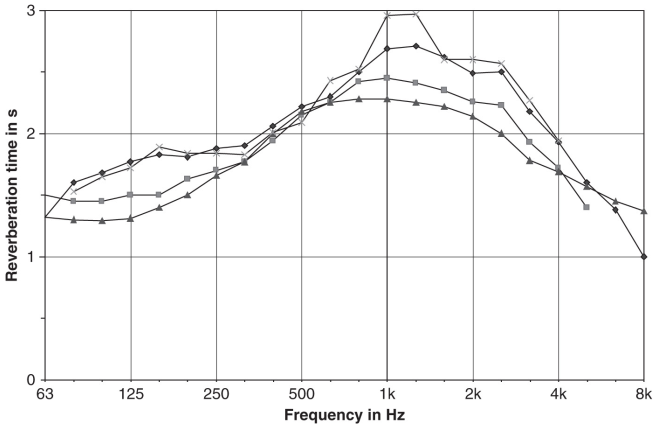

Figure 15. *Reverberation times measured in the Jesus-Christus-Kirche between 1952 and 1963; seating and occupation with varying music ensembles [2, 13].*

into the range of maximum energy emission from speech according to Figs. 7, 9 and 11 or popular music according to Fig. 6.

In the very complex process of room modes interfering with speech and music at least four detrimental effects play an important role:

- The room resonances can change the character of the phonemes in speech (Figure 11) and the tonal structure in music (Figures 2-5),
- discrete lf modal amplification can mask any more valuable information contained in the mid-frequency sound (Figure 12),
- the positive “cocktail party” effect, which at least for binaural listening supports mutual understanding in group conversations and ensemble play without raising emissions, may be grossly invalidated by this strong room response [13, Sect. 11.3.3],
- as an extremely unwanted result, a kind of *Lombard*-effect triggers an almost unavoidable “loudness spiral” to set in for any group communications [13, Sect. 3.4 and 11.4].

Depending on the respective dimensions of the room, these modes are irregularly distributed over frequency. As such they can never help and support any music or speech performance in the room. They disturb any sound spectrum, reduce its clarity or intelligibility, and give rise to high self-generated sound levels in all kinds of communication processes in the room, be it in group tuition or ensemble play. Suitable broadband absorbers can thus not only physically damp a sound field but also physiologically reduce the sound emissions from humans “at the source”.

Again a model example can demonstrate how one may turn an acoustic torture-chamber into a relatively quiet room, provided that its users are aware of the potential noise problem created by them. A private University of

Media and Communication in Berlin-Kreuzberg rented a few spaces of different sizes as classrooms and a seminar room, which was also to be used as library, in addition a conference room and a large cafeteria in a restored historic building complex of a former printing plant. The distinguishing feature of the beautiful rooms with impressively high ceilings of about 3.8 m enclosed by very massive walls was a multiplicity of enormous concrete girders (0.4 m deep below the concrete ceiling, see Figure 16). Shortly after classes started, the complaints of both the students and the professors demanded immediate retrofitting. Of course, as always in such cases, requiring the best right away and at no cost!

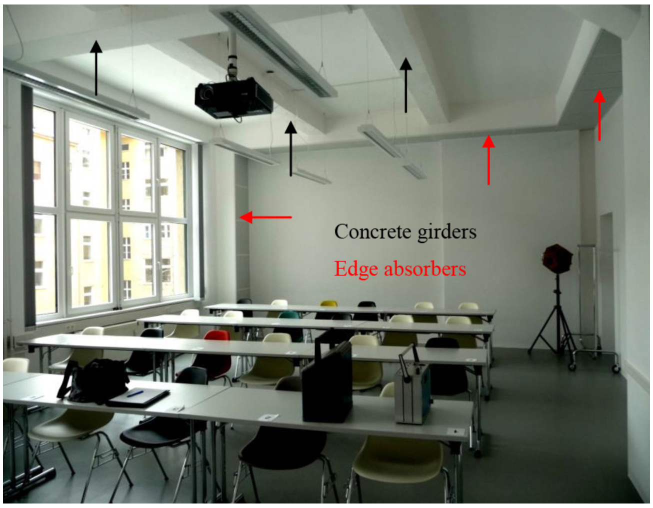

Figure 16. Acoustic retrofitting of a classroom at the University of Media and Communication in Berlin-Kreuzberg with vertical and horizontal edge absorbers [13, 14]

The reverberation time in the various rooms rose, as is usual in such structural circumstances, from 1.5 s at 4 kHz to 4 s at 100 Hz, see fig. 17. The option considered by the investor and landlord of the building was an “acoustic ceiling”, however this would have made it impossible to attain the reverberation time of about 1 s, preferably constant down to 63 Hz, as required according to Figure 13 for this purpose with a room volume of less than 300 m³. At best about 0.5 m wide backfilling with an at least 200 - 400 mm thick damping layer in the ceiling cavity behind an acoustically sufficiently absorptive or transparent mineral-fibre suspended ceiling might have fulfilled the needs. However, against such massive retrofitting were not only the old factory halls´ very attractive architecture, but also the tight budget and schedule of the tenant.

The girders finally provided the design motif of about 400 mm deep edge absorbers according to [13, Sect. 10.3] and [15], making a full-surface suspended ceiling with many openings and conduits for lighting, cables and channels unnecessary. Starting with a 272 m³

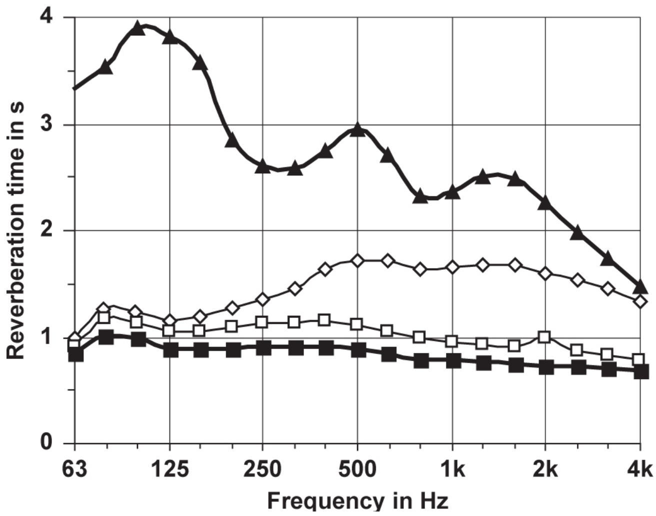

Figure 17. Reverberation times in two similar classrooms without (▲), respectively with edge absorbers according to Fig. 16; unoccupied (◊), estimated with 25 users (□), and with additional working utensils (■)

large classroom, about 400-600 mm wide edge absorbers, always adapted to the structural situation, were installed horizontally under the ceiling over a length of about 25 m on the three windowless walls and vertically at one edge of the room, see Figure 16. The cavity of the edge absorbers enclosed on one side by plasterboard and on the other by perforated sheet-metal cassettes (backed with fibre-fleece) was filled with mineral wool.

After carefully puttying all the wall and ceiling transitions, two coats of the same white paint as on the walls and the ceiling were applied to these installations to ensure that the users would hardly notice the measures when they came back after a short Christmas break, see Figure 16. Compared with the reverberation time of a similarly built room with a volume of 254 m³, an enormous drop in the low-frequency reverberation from approximately 4 s to somewhat above 1 s is noticeable. If the absorption by about twenty-five persons is taken into account and the additional damping by the clothing, bags and instruments that they bring with them into the room, a reverberation time of constant 1 s is yielded, considered almost ideal for rooms of that size used intensively for communication. All users were satisfied and in the meantime several other spaces were also retrofitted in the same manner.

7. CONCLUSIONS AND OUTLOOK

Two sets of objective quantitative analyses were presented which document the character and strength of lf components in music (Sect. 2) and speech (Sect. 3). Their detrimental effects on the clarity and intelligibility (acoustic transparency) of any sound reception is due to their masking the most valuable mf and hf part of the spectra emitted and transmitted in the room (Sect. 4). The representative architectural example with excellent acoustics for all kinds of performances and recordings in Sect. 5 will be followed by the discussion of a number of baroque churches and audio studios in a companion paper. In this context a most recent publication [21] of numerous European rock and pop venues will be evaluated. Another follow-up paper will dwell on practicable methods of damping the bass sounds as much as ever possible in smaller enclosures for communication and tuition. The somewhat novel concept exemplarily applied in Sect. 6 is supported by another more recently published article [22], which reports speech intelligibility scores in a simulated classroom dependent on the lf frequency characteristics of noise and reverberation time. A Swedish author also arrives at very similar conclusions for educational premises as expressed herein, see [23].

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The economic valuation of aircraft noise effects: a critical review of the state of the art

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ABSTRACT

The effects of Aircraft noise on health and quality of life are complex and require a comprehensive understanding about all intervening factors, apart from pure acoustical ones. Quantification and monetisation of the effects have taken on significance as a major field of study with important implications in policy making and business management.

A number of good quality studies have been conducted to quantify the monetary values of the effects of aircraft noise. The WHO report that calculated the burden of disease from environmental noise is one of the most important (1). Last year, the Civil Aviation Authority produced a report that proposes a methodology for estimating the monetary cost due to sleep disturbance from aircraft noise (2). These studies have enriched the understanding of the magnitude and complexity of this matter. However, several gaps remain, challenging decision making on aircraft noise management.

This article aims to provide a comprehensive review of the valuation of the effects of aircraft noise on human health and quality of life, and its implications within noise policy and sustainable airport operations.

1. INTRODUCTION

The quantification of the effects of aircraft noise on health and quality of life and the associated monetisation of those effects has taken on significance as a major field of study with important implications in policy making and business management.

This is relatively new area of study that has been developed independently for each type of effect analysed. It has emerged as a key issue in the sustainable aviation policy agenda as the industry continues to growth. Nevertheless, limitations on the scientific evidence base to establish causal relationship and thresholds have prevented the calculation of accurate monetary values [1]. Our latest research explores this same issue [2, 3].

This paper aims to provide a comprehensive review of the valuation of the effects of aircraft noise on human health and quality of life and its implication within UK noise policy and sustainable airport operations. We present monetary estimates for selected London Airports as a reference for future calculations, which should be considered as indicative only. We emphasize that these values should be used to enhance understanding of trends rather than absolutely quantify values.

We argue that monetisation of aircraft noise effect is a very complex process requiring complex system of policies. There is no single universal policy tool that can give solutions to all concerns. Aircraft noise management is a context dependant process: there is no silver bullet and it requires the interaction of academics, practitioners and policy makers.

2. RELEVANCE OF MONETISATION AND UK AVIATION POLICY

The worldwide air transport industry is expected to grow by 5% to 6% over the next 20 years. In the UK, forecasts predict a significant growth in demand for aviation between now and 2050, bringing the London airport system under very substantial pressure in 2030 and exceeding capacity by 2050 [4]. This forthcoming growth leads to important economic benefits that will continue to boost UK economic prosperity and the local economy of surrounding airport communities. However, it will also leads to negative side-effects on the environment and local people.

Noise has been identified as the most important issue by far for local communities above safety, air pollution or local employment [5]. This has put noise on the top of management and political agenda, urging a better understanding of the extent of aircraft noise effects and the role it plays within a sustainable aviation policy.

In 2012 the UK Government set up an Independent Commission tasked with identifying and recommending options for expanding UK airport's capacity. Three shortlisted options were announced at the end of 2013, two at Heathrow and one at Gatwick Airports as possible locations for a new runway. The objective of the Government is to strike a fair balance between the negative impacts of noise and positive economic impacts of flights [4].

The Commission is undertaking a Sustainability Appraisal [6] for those three options, which incorporates monetising effects from aircraft noise on annoyance, sleep disturbance and cardiovascular diseases. After consultation, the Commission recognised the limitations of their initially proposed methodologies, in particular relating to hedonic pricing for monetising aircraft noise annoyance. In turn, it determined to follow the Disability-Adjusted Life Years (DALY) approach presented in the latest WHO report [7].

Monetary values of aircraft noise effects can provide a common language to assist sustainability appraisal and policy-making and analysis. They also enable comparison and contextualization of noise in sustainability policy and management, by helping to understand the balance between benefits and negatives effects of aviation. Monetary values seem to appear as a useful tool in balancing the cost and benefits of airport operations and their externalities.

3. AIRCRAFT NOISE EFFECTS-OVERVIEW

Human response to noise is very complex and varies between people and places. The extent of the response is influenced by many elements, besides the pure acoustical ones, such as personal, attitudinal and social factors.

The link between noise effects and potential impacts is neither simple, nor linear, as commonly presented. It depends on how one effect can modify another, the cumulative exposure and individual sensitivity to noise, the risk factors associated with health conditions and the influence of modifiers and cofounders factors [8]. This result in a complex web of pathways between noise and health, meaning there is no simple cause-effect model between aircraft noise exposure and health.

The evidence base that supports a link between each particular health outcome and noise exposure has developed independently. Table 1 presents the strength of evidence of effects of aircraft noise on health, in terms of specific cause-effect pathways. This table is based on author's reviews of key international guidelines from WHO and European Commission [1, 7, 9, & 10]. The standardized evidence categories are those used by the WHO.

4. ECONOMIC VALUATION OF AIRCRAFT NOISE EFFECTS

Economic valuation of environmental effects on health and quality of life is a recent field of research which a burgeoning importance over the last years.

In the UK, the Interdepartmental Group on Cost and Benefits Noise subgroup- IGCB(N), a DEFRA led group, was established to provide advice on the economic evaluation of noise and ensure that noise impacts are appraised consistently. The IGCB(N) has provided guidelines on effects that can be part of a valuation methodology [11], as follows:

- Acute Myocardial Infarction (AMI) effects can be monetised using the 2006 Babisch dose-response function. Policy makers must be mindful of the uncertainties associated with this curve.
- New research has updated previous recommendations on Hypertension effects [12]. This study proposes a methodology to monetise the effects of environmental noise hypertension outcomes.
- Quantification of sleep disturbance impacts is possible for policy appraisal but evidence is not sufficiently developed to monetise these quantified effects. This is a priority area for monitoring policy-oriented research.

In order to define whether or not is possible to include specific noise related effects as part of an economic valuation framework it is fundamental to have:

- A sufficient strength of evidence that supports the link between each particular health outcome and noise exposure
- Robust dose-response relationships to quantify the link and ideally accounts for causality
- A monetisation methodology appropriate for each effect
- Analysis and interpretation of results

This can be understood as the basic process to follow when planning and undertaking monetisation of noise effects. In order to responsibly orient noise management

Table 1. *Summary of strength of evidence that supports an association*

Health Effect		Strength of evidence	Issues
Annoyance (indirect; psychological, psychosocial)		Sufficient	Complex interaction with other health effects and non-acoustic factors. Debate on metrics and scope of analysis
Sleep disturbance (indirect; psycho-physiological)	Awakenings	Sufficient	A number of awakenings are normal. No agreement on threshold levels
	Self-reported	Sufficient	Subject to bias
	Long term effects and performance	Inadequate / Lacking	Complex mechanisms underlying long-term effects. No conclusive evidence of decrements in chronic objective long term effects
Cardiovascular (indirect; physiological)	Acute Myocardial Infarction – AMI Hypertension Coronary Heart Disease	Sufficient	Aircraft noise may be a risk factor for CVD, but no causal link has been conclusively proven. No evidence of effects on children Importance of confounding factors
Cognitive development (indirect; physiological)	Adults	Inadequate / Lacking	Lack of data; no firm conclusions can be drawn
	Children	Sufficient	Evidence from primary school reading age and recognition memory in the short term. Uncertainties on the existence of long-term effects. The scale of effect is relatively small compared with other "life events"
Mental health (indirect; psychological)		Lacking	Some evidence of symptoms, but not of severe clinical disorders
Hearing impairment (direct; physiological)		None	No effects at environmental noise levels <75dB (A)

What do we need for monetisation?

or policy decisions, it is important that policy makers are aware of the many limitations and uncertainties that result may have. It is important to note that this is complex field of work that requires the interaction of academics, practitioners and policy makers.

4.1. Approaches for economic valuation

The monetisation of aircraft noise effects can be split in two types of approach.

One approach relates to the cost of lost productivity caused by exposure to aircraft noise, which commonly requires the estimation of the Disability-Adjusted Life Years (DALY) as suggested by the WHO. This is an approach used for quantification and associated monetisation of aircraft noise effects on health. The IGCB(N) recommends the UK monetary cost per DALY to be £60,000 [11]

The other approach relies on the estimation of the willingness to pay to avoid (WTP) or to accept (WTA) a certain level of noise, which can be undertaken using either

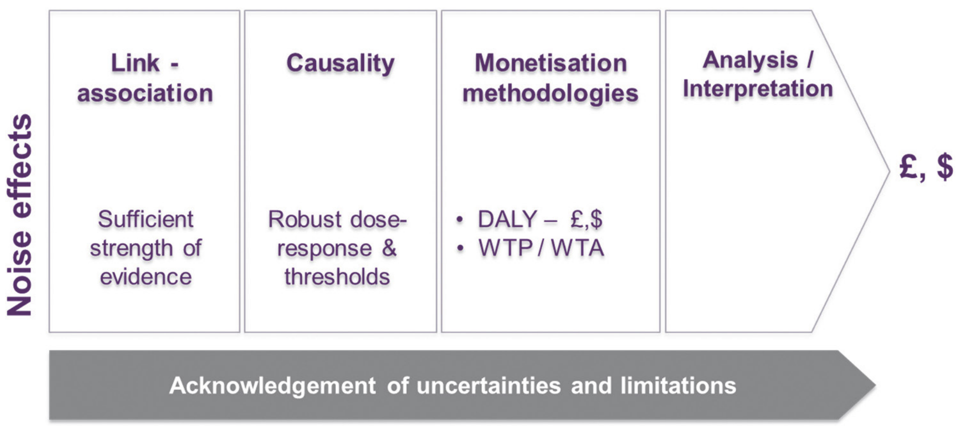

Figure 1. *Monetisation process.*

revealed preference (e.g. hedonic pricing, HP) or stated preference - SP (e.g. contingent valuation) techniques. This approach is commonly used to monetise the "cost of aircraft noise", without a specific reference to any particular effect.

Figure 2 summarises the above-mentioned approaches for monetising the effects of aircraft noise on health and quality of life.

The following sections of this paper outline a general framework for monetising aircraft noise effects and provide specific in depth analysis for each particular effect.

4.2. Annoyance

In the UK annoyance is currently one of the most debated issues regarding aircraft noise effects. Concerns around the metric used, the validity of noise contours in L_{Aeq} to estimate people annoyed and potential increases in noise sensitivity, are key elements that add complexity to the debate.

Recent studies concluded that no annoyance curve can represent the annoyance situation of all airports, highlighting the validity of official curves used in the EU and US for such a process. It shows that less than 20% of the variance in annoyance judgments can be explained by acoustical variables [13, 14].

There have also been important developments in recent years with the emerging concept of Community Tolerance Level [15]. This concept is currently being applied in a major revision of the International Standard ISO 1996, expected to be published at the end of 2015 [16]

Generally there are two approaches for monetising the effects of aircraft noise on annoyance; one is the estimation of the Burden of Annoyance and other is the calculation of the WTP / WTA. Nevertheless, the UK Airports Commission established the Burden of Annoyance as the approach to follow for policy appraisal of annoyance effects from aircraft noise [6]. This paper updates previous publications [2] and follows the same approach to that suggested by the Commission.

The Burden of Annoyance combines exposure data, with the EU Position Paper on dose-response relationship between aircraft noise and annoyance and a disability weight (DW) that ranges from 0.01 -0.12, with a central value of 0.02 [7].

The main limitations of this approach are the use of a unique relationship to explain annoyance situations across all airports and the high degree of uncertainty due to the large range for the DW. There are doubts about the extent to which monetising annoyance make sense to noise policy making. How to weight universally a subjective and self-reported impact comes as one of the most concerning issues around these methodologies.

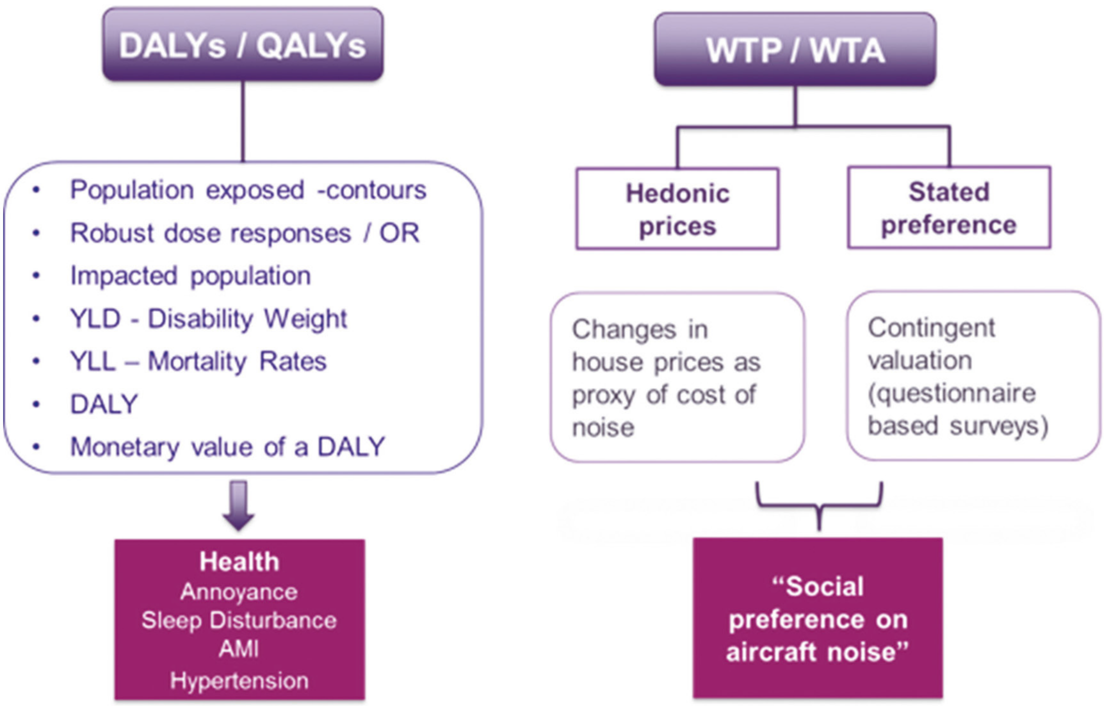

Figure 2. *Approaches for monetisation.*

4.3. Sleep Disturbance

Sleep disturbance-related effects are a well-developed area of research but there is currently no agreement on a single dose – response relationship to inform an economic valuation methodology [17]

A recent paper presented by Basner [18] in ICBEN 2014 Conference showed half of the variance in response is due to inter-individual differences, meaning that the relationship between night-time aircraft noise and sleep disturbance depends on individual noise sensitivity. The same study developed different relationships for specific noise sensitivity level. This may have important implications in night noise policy and regulation and International standards.

The Civil Aviation Authority in the UK proposed in 2013 a methodology to evaluate the loss of productivity resulting from sleep disturbance [19]. This uses the percentage highly sleep disturbed function (%HSD) for L_{night} from the EU Position Paper on night time noise [20], derived from Miedema work [21]. The basic principle is to determine the additional cost or net benefit of a proposed policy measure compared with a baseline using DALYs approach.

A major limitation relies on the use of a unique relationship to all airports and cases. There are also uncertainties associated with the high degree of unexplained variance and bias that results pose. This is due do the large uncertainty interval for the disability weight (which ranges from 0.04 to 0.1 with a central value of 0.07) and because the %HSD is based on self-reported studies. The uncertainty in the dose-response relationship was not considered in the analysis of DW.

4.4. Cardiovascular disease: Acute Myocardial Infarction and Hypertension

According to Babisch [22], the hypothesis that chronic long-term exposure to environmental noise increases the risk of cardiovascular diseases has been confirmed in large epidemiological studies. However, the relationship specifically to aircraft noise is much less well understood.

Recent studies have contributed to both strength of evidence and definition of better and robust dose-responses. However, there are many confounding factors that have not been isolated at this time [23, 24].

Acute Myocardial Infarction

Cardiovascular effects related with Acute Myocardial Infarction- AMI can be monetised by using the 2006 Babisch relationship, which establishes a NOAEL of 60 dB L_{day}, to assess the additional risk with raising road traffic noise levels [25]. According to Babisch, apropos aircraft noise, no other alternative exists at present than to take the AMI risk curves derived from road traffic noise studies as an approximation for aircraft noise.

Monetisation of AMI effects can be done by using the DALYs approach [7].

The authors warn about the multiple uncertainties around this function, and the risk that noise management decisions based on this link might not have the expected results. Most of the uncertainties are related with the variability on responses across population due to differences in individual noise sensitivities, the role of habituation, effects from air pollution and other non-identified confounders, and applicability of the curve against other noise sources.

Moreover, recent research shows a large number of technical and scientific uncertainties that prevents using this curve to establish threshold levels; meaning that this curve cannot be used to establish a NOAEL/LOAEL. More studies are needed examining the full range of exposures to better define the dose-response relationship. [26]

Hypertension

The latest study from Harding [12] has contributed to IGCB(N) work, by identifying three noise- related hypertension (HT) outcomes (AMI, stroke and dementia) and proposing a method for monetisation of those effects using the quality adjusted life years (QALY) approach.

In their methodology, Harding used van Kempen & Babisch 2012 pooled estimate as a first step in quantifying the link between environmental noise and HT. To quantify each outcome, the risk of HT associated with an increase of noise levels above 55 dB $L_{Aeq\ 16\ hrs}$ was combined with the risk associated with HT for AMI, stroke and dementia.

Monetisation was undertaken using the “QALY loss” approach. This is a similar measure to DALYs, which instead of disability weights (DW) uses health weights. This study estimated that the cost of additional HT-related cases due to environmental noise exposure in the UK was around £1.09bn, providing and insight into the scale of health impacts due to environmental noise exposure. If using Babisch & van Kamp risk estimates, results increased to £2.53bn. This is because the proportion of population exposed above recommended levels is greater for L_{den} than for $L_{Aeq.}$

The main limitations of this methodology are the use of non-aircraft risk rates if using van Kempen & Babisch and uncertainties on availability of data.

5. ESTIMATION OF MONETARY COSTS FOR SELECTED UK AIRPORTS

We have estimated the change in the monetary cost of aircraft noise on cardiovascular disease (AMI), sleep disturbance and annoyance using DALYs estimation for selected London Airports: Heathrow (LHR), Gatwick (GTW) and Stansted (STN) between 2011 and 2006.

Due to limitations on the availability of information, it wasn't possible to undertake estimates for other London or UK Airports.

5.1. Noise exposure data

For all three airports, we have used L_{den} and $L_{night,\ 8h}$ 2006 noise maps contours produced and published by DEFRA according to the Environmental Noise Directive, END, and English Regulations [27]. We have used the 2006 and 2011 Strategic Noise Mapping Contours for each airport, produced by the Environmental Research and Consultancy Department (ERCD) of the CAA in the UK [28-33]. These contours are based on air traffic movements over the entire year. Data published at these reports are the same than DEFRA data.

Since data was only available at 5dB steps from 55dBA to 75dBA for L_{den} and $L_{Aeq,\ 16hrs}$, and from 50dBA to 70dBA for $L_{night,\ 8h}$ midpoints values were chosen for each band in order to undertake estimations.

These reports use different data sets for population between 2006 and 2011. For 2006 noise maps, the population data is based on 2001 UK Census, updated in 2005. For 2011, the population data is based on the 2011 UK Census. Although this limitation, this was the only consistent information available across airports that allowed reasonable comparison and aggregation.

5.2. Methodology

We used the methodology proposed in this paper, including the corresponding dose-responses for each effect in the estimation of the DALYs. We have adopted the recommended UK monetary cost per DALY of £60,000 [11, 19].

5.3. Results

Acute Myocardial Infarction

To estimate the number of additional AMI cases resulting from noise exposure, we have used a low threshold of 55dB LAeq, 16hrs which according to Babisch no effects were found below this level [25].

An AMI risk of 0.0596%, based on the UK AMI risk of death (72%) was used. We have assumed that the underlying prevalence of AMI in UK population is the same for each of the populations analysed. To estimate the number of DALYs a disability weight (DW) of 0.405 was considered. An average of 11 years loss of life and a mean disability weighting of 7.94 was used for AMI mortality [7, 11, 19].

The monetary cost due to AMI effects from aircraft noise in the three London Airports was valued at around £133m for 2011 compared with £142m in 2006. There is net change in cost of -£9m (-7%).

Sleep disturbance

Despite the multiple limitations mentioned in the previous section regarding the use of a unique dose-response, we have estimated the monetary cost of sleep disturbance due to aircraft noise from London Airports, using the EU official curve. These estimates can just indicate a trend on cost evolution across years, instead of absolute cost.

Due to limitations on the availability of the data, the lower threshold used for these calculations was 50dBA $L_{night,\ 8h}$.

The monetary cost due to sleep disturbance effects from aircraft noise in three London Airports varies in range of £53m to £133m in 2011 and £53m to £132m in 2006 depending on the DW. Using the central value of DW at 0.07 as recommended by WHO [7], monetary estimates were valued at £93.4 m for 2011 and £92.1m in 2006. This shows a marginal change of 1.4% in the cost over 5 years, mainly due to a decrease in the population exposed to aircraft noise during night.

Annoyance

As in the case of sleep disturbance, in order to have a broad understanding of trends in cost of aircraft noise in London, we have provided calculations using the EU annoyance dose-response curve and Burden of Annoyance methodology. As mentioned above these estimations are full of uncertainties and limitations that must the considered when interpreting and using these results.

Due to limitations on the availability of the data, the lower threshold used for these calculations was 55dBA L_{den}.

Due to large uncertainty interval for the DW, monetary cost due to annoyance from aircraft noise in the three London Airports varies in a range of 12 times between the lowest and highest value. There was almost no significant change between 2006 and 2011 estimations. For both years, the monetary cost of aircraft noise annoyance at selected London Airports varies between £77m to £925m. Using the central value of DW (0.02), the cost was estimated at £154m for both years.

This evidences the high degree of uncertainty and variability that should be considered when interpreting and using these results. It also raises questions about the reliability and accuracy in the results and to what extent makes sense to monetising annoyance effects.

All the results presented in this paper must be used as indicative only and to provide some insight into the scale of the health impacts from aircraft noise exposure at three London Airports. No definitive conclusion can be given on an absolute cost of aircraft noise effects around these Airports. Also, we note multiple caveats associated with this process when interpreting these results.

6. POLICY IMPLICATIONS AND CONCLUSIONS

Monetisation of aircraft noise effect appears as a critical issue for noise policy makers and private airport operators to facilitate decision-making. It can provide a common language to assist noise policy making; it helps to understand how noise can affect human's health and quality of life and can help to establish research priorities. Also, monetary values can vindicate the need for policy interventions on this matter and could provide economic indicators and signals for the design of sustainable and efficient noise policies and instruments.

However, it is a very complex process, due to the complex nature of noise and how it affects people, the difficulty in establishing causal relationships and the multiple uncertainties associated with valuation methodologies.

We argue that monetary values should be used to enhance understanding of trends rather than absolutely quantify values.

Some challenges remain in the process of understanding and applying monetary values of aircraft noise effect within noise policy, such as how to aggregate the different cost in relation to understanding the balance between positive and negative impacts that aviation can bring.

We have estimated the cost of aircraft noise on AMI sleep disturbance and annoyance at three London Airports. All the results presented in this paper must be used as indicative only and to provide some insight into the scale of the health impacts from aircraft noise exposure at three London Airports. No definitive conclusion can be given on an absolute cost of aircraft noise effects around these Airports. Also, we note multiple caveats associated with this process when interpreting these results.

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Understanding amplitude modulation of noise from wind turbines: causes and mitigation

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ABSTRACT

Modulation of the noise or "swish" is always present close to a rotating wind turbine, and represents an inherent and well-understood feature of wind turbine noise. However, on some wind farm sites higher levels of modulation have sometimes been measured in the far-field, with characteristics which cannot be accounted for by standard models. The authors headed a multidisciplinary research project on the subject which comprised theoretical and experimental investigations. After identifying the potential causal mechanisms for different types of modulation, a mechanism for this atypical or "other" modulation was proposed: the occurrence of stall on the blade only during part of the rotation. The resulting predicted directional features were found to be consistent with evidence from field measurements. An objective method to quantify levels of modulation was also developed and applied to large datasets, and shown to work well in practice. Subsequent work is also presented showing the results of modifications of the blades and/or operational characteristics of wind turbines which resulted in a clear reduction of the far-field AM. This provides further confirmation of the source mechanism identified as well as pointing towards the development of practical mitigation measures.

1. INTRODUCTION

The issue of amplitude modulated noise (often referred to as "blade swish" or "AM") arising from the operation of wind turbines is presently receiving a high focus of attention. Whilst the acceptability of audible noise from wind turbines continues to be the subject of considerable debate, the specific issue of AM has been specifically considered in a number of studies which have reported disturbance from this feature of the wind turbine noise. In some cases, however, the observed characteristics of the AM could not be explained by existing, validated theoretical models of 'blade swish'. This has led to speculation as to the potential existence of quite different source generation mechanisms, and/or propagation effects, which could explain the observed differences between the well understood and quite "normal" blade swish noise and this other manifestation of AM noise. It was also identified that there was no generally accepted metric for describing and quantifying AM noise in general, and that the knowledge of the subjective response to it was limited compared to, for example, tonal noise which has been the subject of extensive work.

To progress these issues a research project comprising theoretical and experimental investigations into the amplitude modulation of noise from wind turbines was commissioned, with the results published in late 2013. This article discusses the results from this project in terms of the causal mechanisms identified for different types of amplitude modulation noise from wind turbines, including supporting evidence from field investigations and objective methods developed to rate the modulation. The subjective response to this phenomenon in terms of annoyance was also considered as part of the project but results of that element of the work not set out in this article. Additional measurements are also presented which further support the results of previous investigations.

2. CONTEXT AND OBSERVATIONS

The aerodynamic self-noise generated by the interaction of flow turbulence and the surfaces of a wind turbine's rotor blades is said to be amplitude modulated when its level exhibits periodic fluctuations; for a fixed observer this will be at a rate corresponding to the frequency at which each rotor blade passes a fixed point (the "blade-passing frequency"). This amplitude modulation (AM) is always detected close to a rotating wind turbine, and is commonly described as "swish". The principal source of audible noise from the blades is "trailing-edge noise": caused by the interaction of turbulence in the boundary layer with the trailing (thinner) edges of the rotor blades (Figure 1). Because this noise source has particular directional radiation characteristics, even in a smooth laminar flow, an observer close to the wind turbine would experience periodically varying levels of noise related to the passage of each blade. AM resulting from this trailing edge noise directivity effect was therefore termed "Normal AM" (NAM), it being an inherent and therefore "normal" feature of wind turbine noise.

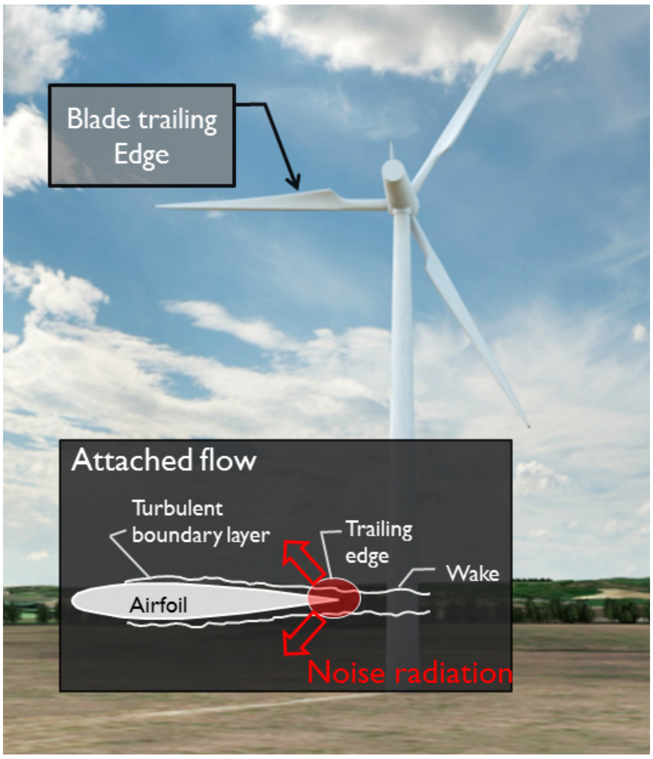


Figure 1. Illustration of a turbine blade trailin edge in normal opertion and the preferential noise radiation of the noise generated.

This characteristic blade swish has been explained theoretically and demonstrated by measurements prior to the current research (Oerlemans and Schepers, 2009). This research has confirmed the existence of periodic variations in overall noise level (i.e. "blade swish", or NAM) of typically 5 dB(A) to 6 dB(A) in the crosswind direction from the rotor as each blade travels in a downwards trajectory towards an observation point located close to the ground. Theory suggests that this NAM would not be expected to be apparent (or with less than 3 dB(A) variation) either downwind or upwind of the rotor. Such theoretical expectations have been validated by measurements in both in the near-field and far-field of wind turbines.

In the UK, a previous study undertaken on behalf of the UK Government by the University of Salford (Moorhouse, 2007) was initiated following complaints of what was initially believed to be problematic levels of low frequency noise arising from a limited number of operational wind farms. It was, however, determined that it was the modulation of the broadband noise from the turbines, at the rate of the turbines passing a fixed point (or "blade-passing frequency"), *i.e.* AM, which was causing the complaints (Hayes McKenzie Partnership, 2006). On other wind farm sites in Europe, relatively high levels of AM noise were reported to have been detected in the far-field, down-wind from wind turbines (see for example van den Berg, 2004 and Di Napoli, 2011). In these cases the magnitude of the variations in noise levels was reported to be higher than that predicted due to NAM (5 to 10 dB), and the noise was generally described as being more impulsive in character, better described as a "whoosh" or "thump" rather than a "swish" (Van den Berg, 2004 and Bowdler, 2008), with increased dominance of frequencies in the 200-400 Hz region (Stigwood, 2013). These occurrences cannot be accounted for by the established trailing edge noise mechanism of normal blade swish (NAM), and it was therefore concluded that other source generation mechanisms and/or propagation effects must be responsible. AM phenomena with characteristics falling outside those expected of NAM became termed "Other AM" (OAM).

The prevalence of wind turbine OAM noise in the UK is disputed, but it has nonetheless become a recognised phenomenon and has formed the subject of several publications and presentations at international conferences in recent years. As an example, the review by Bullmore *et. al.* (2011) summarised examples of published reports at that time. However, whilst the existence of OAM was relatively widely acknowledged at that time, the causal mechanisms of OAM were not understood and, as a consequence, no specific information was available to guide operators or manufacturers towards the likelihood of occurrence of OAM or appropriate remedial actions to mitigate its effects in circumstances where it did occur.

3. CAUSES OF OAM

The existing model of NAM referenced above (Oerlemans and Schepers, 2009) was further developed as part of the present project to account for non-uniform flow into the rotor disc (Oerlemans, 2011). This study, as well as the independently reported work of Boorsma/Schepers (2011), concluded that the variation of wind speed across the rotor disc due to the effect of increased vertical wind shear cannot, in itself, lead to increased modulation or account for the observed characteristics of OAM.

The model was then further developed (Oerlemans, 2011) to include the effect of the separation of the flow from the blades for part of their rotation, or *transient blade stall*. In the model, partial stall was triggered for part of the rotation by a vertical wind gradient (or wind shear): the increases in the inflow wind speed increased the effective angle of attack of the flow onto the blade. It was recognised, however, that other flow non-uniformities (such as turbulence, the wake of another turbine etc.) could trigger similar effects. Whatever the cause of such localised blade stall, the turbulent air in the stalled region creates an increase in noise generation with a lower frequency content and different directivity characteristics when compared to trailing edge noise. Thus the momentary and periodic increase in noise level created when such flow separation occurs over a small area of each turbine blade in one part of the blade's rotation only (for example as it passes over the top of its path: see Figure 2). This results in modulation with significantly different characteristics to NAM; in particular, the change in directivity of stall noise is predicted to result in significant modulation levels in upwind and downwind directions (Figure 3).

Figure 2. Illustration of detached flow over part of the rotation (partial stall).

As downwind directions are those in which the highest overall noise levels are generally experienced in the far-field of the turbines due to favourable propagation conditions, it is to be expected that OAM noise will most likely be present under such downwind propagation conditions, and this is consistent with observations in the field. Radiation of OAM in the upwind direction is also predicted and has been observed in the far field under some circumstances (but less frequently).

The foregoing combination of a transient stall source generation mechanism and its associated directivity effects, taken together with propagation effects, was identified as potentially explaining the different acoustical characteristics and predominantly downwind impact of OAM when compared to the more limited and predominantly crosswind impacts of NAM. Depending on characteristics of the stall region, increased modulation amplitude and additional lower frequency content may also be present. Of the potential OAM "source" effects considered the prime candidate was therefore identified as transient separation of the blade airflow (or stall). In order to investigate this possibility further, additional targeted field investigations were undertaken as part of the research project, with one example summarised below.

4. EXPERIMENTAL VALIDATION WORK

Detailed measurements were made at a site were "Other AM" had been experienced in order to further study the characteristics and directivity of this noise feature. Levels of AM were measured at different distances from the turbines, at a combination of near- and far-field locations (at distances of 1, 3 and 10 rotor diameters from the nearest turbines) in different directions. Detailed anemometry and turbine operational data were also captured at resolution of 1 to 3 seconds.

A detailed analysis of the modulation identified in specific periods, including phased shutdown of adjacent turbines, showed that OAM could occur with each turbine operating in isolation, thus appearing to exclude interaction of the flow between the turbines as a dominant causal factor. During periods of marked modulation no elevated atmospheric turbulence was found to be present, which further excludes turbulence ingestion as a direct source mechanism. This observation is consistent with theoretical considerations (Smith, 2012).

Higher levels of modulation were identified as being experienced with increasing distance from the turbine, with a peak in this instance at approximately 10 rotor diameters away from the turbine followed by a decrease thereafter. This was broadly consistent with the observations of, for example, Di Napoli (2011). Ground reflection effects could have affected the measurements at intermediate distances to a degree, as, at the measurements height (1.2m above the ground), these interference effects would in theory create a reduction in the 300Hz region which was dominating the observed modulation.

The observed directivity of the OAM in the far-field was found to be highest downwind and more limited cross-wind, which was the opposite of the situation in the near-field and as expected for NAM. See, for example,

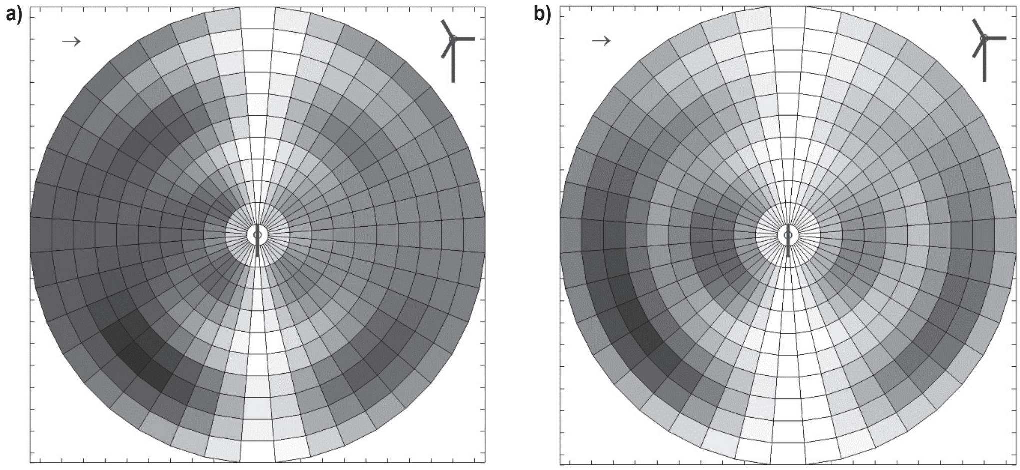


Figure 3. Sample instantaneous noise footprints calculated for moderate wind shear (aerial view, wind blowing from left to right) – white corresponds to low noise levels, and black to louder levels, and variations illustrate the presence of modulation, which is mainly present cross-wind in a) (attached flow) and up/down-wind for b) (partially detached flow). From Oerlemans (2011).

Figure 4 which represents an example of a period of marked and relatively impulsive modulation observed in the far-field downwind location, but simultaneous measurements in the cross-wind direction do not show the same modulation. This observed specific directivity is consistent with the theoretical modelling of the partial stall generation mechanism, which results from the particular directivity of the stall source on the blade. At the same time, in the immediate near-field, the opposite and standard pattern of modulation (mainly cross-wind modulation of no more than 6 dB(A)) was apparent. The lack of strong modulation in the near-field is likely due to source directivity effects.

Periods of OAM in the far-field were examined alongside the turbine operational and meteorological parameters available. The observed modulation levels were strongly variable which suggests the influence of propagation effects. A more detailed analysis revealed a low or sometimes negative correlation with the vertical gradient of wind speed and wind direction experienced across the turbine rotor. In one specific example, a period of relatively strong modulation was observed as the wind speed increased and the wind shear decreased. However, further analysis showed that this high AM period was associated with a relatively rapid variation in the relative angle of flow incidence,

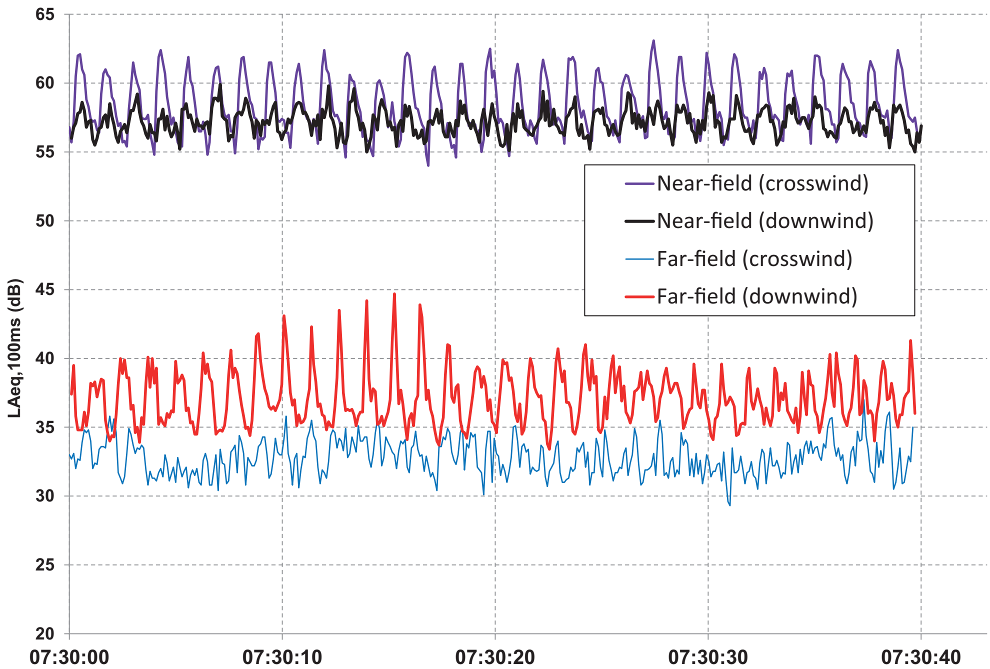


Figure 4. Simultaneous time history of measured LAeq,100ms levels for a sample OAM period showing: two far-field (downwind and cross-wind) and two near-field locations (cross- and down-wind).

which was estimated using operational information from the turbine control system. Further details and results are considered in Cand (2012).

5. DEVELOPMENT OF A METRIC FOR AM

Defining the magnitude of amplitude modulation ideally requires a robust and objective method that is applicable in a repeatable manner to real measured data. In order to be helpful in rating any potential impact of AM, any such method should also be capable of providing a rating "level" which can be meaningfully related to subjective response. The "modulation depth" or difference between the "peaks" and "troughs" of short term measured noise levels, typically utilising the $L_{Aeq,100ms}$ or similar, has often been used to date. Subjective review of "raw" fluctuating noise levels with such resolutions of a fraction of a second is generally not realistically possible under practical conditions. This is due primarily to the compounding effects of non-wind turbine related noise sources such as wind or bird song that may equally vary with time and affect the measured levels of individual peaks and troughs of the AM noise (Bass, 2011).

The key feature of AM that assists in its detection and analysis is the fact that the noise has a periodic character. Fourier-transform analysis techniques of the signal envelope (this signal envelope typically being provided by the $L_{Aeq,100ms}$ or similar) can be used to objectively identify the modulation frequency and then rate the magnitude of the modulation at this frequency. Different variations of such techniques have been used for example by Lee (2009), Vos (2010), McCabe (2011), Lundmark (2011) and Gabriel (2013). White (2012) showed that such methods represent an optimal way of determining modulation parameters in a specific statistical sense, particularly when applied to narrow-band signals. Although such methods show a promising performance in their application to real data, the exact analysis parameters used, the normalisation process and the scope of application are currently not standardised. Recently, the UK Institute of Acoustics published a consultation document on this subject (Bass *et. al.,* 2015) which aims to assist in the selection of an agreed method.

In the research project a Fourier-transform technique was implemented in MATLAB. The sequence of the $L_{Aeq100ms}$ values was used as the signal envelope, for sample blocks of 10s length (with a rectangular window) and de-trended using a polynomial function. The power spectral density (PSD) of the enveloped was then calculated, normalised with a factor of twice the square root of twice the PSD, and integrated over a moving window of 10% of the modulation frequency considered (typically around 0.15 Hz). The value of the local peak in the integrated modulation spectrum at the modulation frequency, which equates to the blade passing frequency of the turbine for samples containing wind turbine AM noise, results in a representative measure of the modulation magnitude: see example in Figure 5.

OAM, where it occurs and its presence has been confirmed, has generally been observed to be infrequent with an onset that cannot be predicted, although in some cases experience indicates that it is more likely to occur under particular wind conditions (i.e. speed, direction or shear). Therefore, detecting wind turbine AM "automatically" in a measured noise

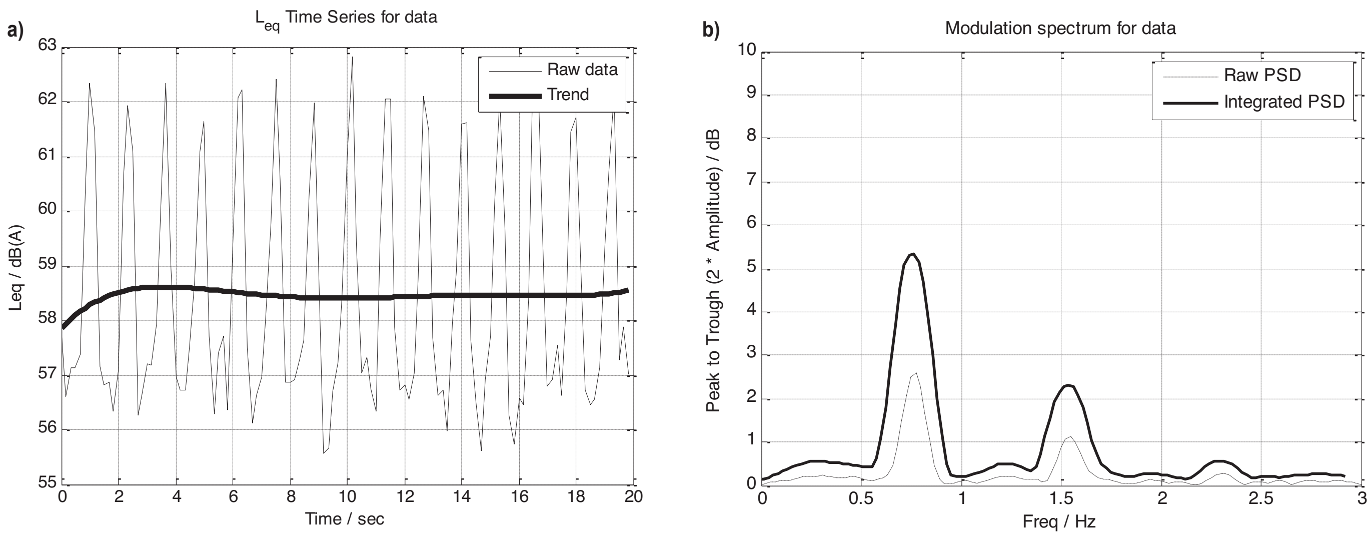


Figure 5. *a) Time history ($_{LAeq100ms}$, arbitrary scale, as a function of time) and b) resulting modulation spectra (as a function of modulation frequency), both raw and integrated, for an artificial AM signal. The peak at the modulation frequency of 0.8Hz is clearly visible in b).*

signal by post-analysis of continuous measurements was considered key. Fourier-based methods were shown in the above referenced research, and in Cand (2012), to be effective. Most sources of extraneous noise are capable of being excluded by applying appropriate signal filtering prior to undertaking the Fourier analysis, in so doing focusing the modulation analysis on the audio frequency bands in which the modulation is most significant and thereby providing a more robust procedure.

6. MITIGATION INVESTIGATIONS

In the absence of techniques such as actual blade surface measurements, it was not possible to positively identify the occurrence of stall as part of the RenewableUK research project described above. However, work by Madsen (2013), undertaken independently of the above described project, provided further support to this hypothesis through the analysis of detailed on-blade measurements and additional theoretical modelling. Madsen also outlined potential mitigation measures which would in theory reduce the potential onset of blade stall and therefore potentially reduce or prevent the incidence of OAM.

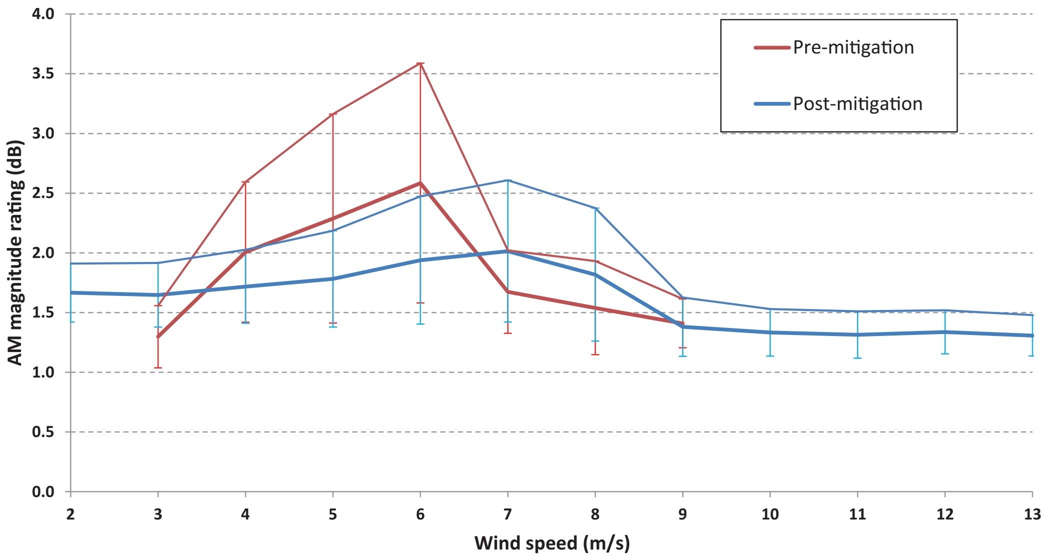
The authors of the present article also undertook additional investigation at sites at which OAM was found to be present and mitigation measures based on the above studies were investigated. The prevalence of AM in the noise was compared before and after the mitigation measures were put in place. This article describes results at one of these sites: a large scale modern wind farm consisting of more than 5 turbines with a generating capacity of more than 2 MW each, situated in relatively flat terrain. Instances of OAM were observed at the site, particularly in conditions of increased wind shear, at two locations both situated approximately 1 km away from the nearest turbines at which measurements were undertaken following complaints. No physical modifications to the turbine blades were made, and mitigation took the form of a modification to the operation of the turbine via changes to the turbine control software. The standard operating pitch angle, describing the rotation of the blade around its axis, was modified with the specific aim of reducing the angle of attack of the flow on the blades (by several degrees) for the wind speed region over which OAM had been detected.

A 01dB Duo sound level meter was installed at each location. The sound level meter equipment is certified Class 1 under IEC 61672 and was weatherproof, with connection to a battery supply to supplement its internal battery and allow for extended periods of operation. The microphone was mounted at a height of approximately 1.2 m to 1.5 m above ground using a tripod mounting, and fitted with a primary and secondary windshield system used to reduce wind-induced noise on the microphone. The A-wieghted L_{eq} and 1/3 octave band noise data was recorded continuously in 100 ms resolution for the period of the measurements.

For the investigation, the above described metric technique, based on Fourier analysis techniques, was used to rate the modulation. It was applied to narrower-band 1/3 octave band signals between 100 and 500 Hz, instead of applying it to the overall A-weighted $L_{Aeq,100ms}$ values. Experience has shown that the analysis of the short-term evolution of the variations in certain 1/3 octave bands can provide a better characterisation of the modulation in many circumstances. This approach also filters out spurious noise sources that occur at higher or lower frequencies than those which dominate the wind turbine noise. The average AM “depth” or dB rating for each of the bands in that range was then averaged to provide a single metric.

Due to the highly variable nature of the wind turbine modulation in the far-field, a statistical analysis was found to be most useful in understanding the measurements. The distribution and variation of the calculated 10s AM metric magnitude values was analysed over each 10 minute period, and then related to the turbine operational data and meteorological data which was available at this resolution. Extended periods which were clearly affected by spurious data were excluded from the analysis: this was apparent from the modulation spectrum as high values not “modulating” at a frequency of around 0.8 Hz characteristic of the turbines. In order to minimise the influence of spurious sources, the analysis was further restricted to late evening or night-time periods only (after 21:00 and before 06:00), and when the monitoring locations were downwind of the wind farm. The dataset was then sorted into 1 m/s wide wind speed bins. In each bin of the filtered dataset, the average and standard deviation of the variation of the dB modulation metric were calculated.

Figure 6 shows the results of the analysis at the one of the locations (similar results were obtained at the second location). It can be seen that a significant reduction in the average modulation rating is apparent in the data following mitigation over the range of 4 to 7 m/s. It was over this range that disturbance was previously noted: the change in the blade pitch angle was therefore designed to be highest in these conditions. The reduction is such that the average + 1 standard deviation results over this range are lower than the pre-mitigation average results.



The foregoing analysis shows how appropriately modified turbine operation can create an appreciable and systematic reduction in the modulation measured at typical residential neighbour distances when compared to data previously acquired during which disturbance was reported. Complaints of noise from the wind farm are understood to have subsided at the site as a result of the turbine operational control changes. The analysis provides objective evidence to support this observation of reduced occurrence of complaints. Further details and additional results are set out in Cand (2015).

7. CONCLUSIONS

The research project, sponsored by RenewableUK and described in this article, identified a likely generation mechanism which would explain specific instances of amplitude modulated (AM) noise which had been observed to occur in some cases at some wind farms in the UK and abroad. This was described as "other AM" as it could not be explained by the standard well-understood mechanism which describes the AM observed as standard in proximity to any wind turbine. Noise modelling showed that the observed characteristics of Other AM could be explained by the flow on the blades stalling for part of their rotation, and this was supported by specific field measurements undertaken as part of the same project.

A number of factors could trigger the occurrence of such partial stall. These factors include: non-uniform wind profiles, for example due to a vertical or lateral variation in wind speed, or a spatial variation of the angle of the wind onto the rotor, where high wind shear or local wind gusts could provide the conditions for this to happen. The onset of stall will in each case depend on turbine-specific blade design and operational characteristics. It is therefore not possible to predict with any certainty whether or not a given turbine on a particular site would generate Other AM.

The identification of this source generation mechanism can, however, aid in identifying operational or design measures which would in theory minimise or fully mitigate the incidence of transient stall, and therefore Other AM, where it is found to occur. The authors undertook specific measurements on operating turbines, both with and without the mitigation applied, which demonstrated that such mitigation strategies are possible and effective in practice. This provided further support of the source generation mechanism identified, as well as the analysis techniques used which were shown to produce meaningful and repeatable results. It is hoped that future turbine designs will aim to minimise the potential for this feature to arise, and that the methods for analysing and rating AM will become standardised in the near future.

8. ACKNOWLEDGEMENTS

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Acoustic discomfort for tertiary-sector employees: issues and means of action for prevention

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ABSTRACT

The numerous tertiary-sector employees who work in open-plan offices are very rarely exposed to damaging noise levels. However, they are subjected to equipment or conversation noise that inconveniences them, tires them, or distracts them. Such noise constitutes discomfort in the form of disturbance and annoyance that it is necessary to assess and then to reduce. To achieve this, various pieces of work have been initiated in France in recent years. In the absence of a regulatory framework, international and French standards are seeking to give guideline values both to company occupational safety and health (OSH) specialists, and also to open-plan office designers so that the acoustic characteristics are consistent with the work that is required of staff. The models for computing ambient sound are being ever-improved in order to assess solutions prior to design, or in order to correct existing solutions. Verifications in the field should include metrology capable of estimating conventional parameters (background noise, spatial decay, and reverberation time) and less conventional parameters (ambient noise, intelligibility, discretion) and to combine those data with surveys taken on employees. Recent studies have shown that the discomfort in terms of disturbance and annoyance is very much linked to the intelligibility of the noise, but that firstly conventional intelligibility indicators are insufficient to assess a decrease in employee performance.

1. INTRODUCTION

INSEE, France's National Institute of Statistics and Economic Studies, estimates that several million employees currently work in the tertiary sector in France, and that a non-negligible proportion (several hundreds of thousands of people) in that sector work in open-plan offices. It is also known that many employees attached to industrial production activities (automobile, aviation, and other industries) are, although not identified as tertiary-sector workers, confined to doing intellectual tasks in open-plan offices. It is therefore extremely important to improve knowledge of this type of workspace when addressing occupational risks and occupational health.

Among annoyances encountered in open-plan offices, noise is complained about unanimously by employees [1]. Whenever work requires intellectual concentration, attention on the telephone, or understanding a speaker (colleague or client), any intrusion of undesired noise into the worker's personal space constitutes discomfort in the form of disturbance and annoyance. Naturally, the majority of the noise encountered in such work spaces is at levels that are sufficiently low not to present any auditory risk. However, the level and the emergence of noise, as well as its spectral or temporal characteristics, or indeed its intelligibility, can rapidly make it annoying or tiring. This observation has led various stakeholders (OSH specialists, occupational physicians, ergonomists, employers, employees, scientists, etc.) to take a growing interest in the problem in recent years.

As a result, much progress has been made. Such progress can be related to standardisation that attempts to give guideline values, to the people recommending the improvements or the designers of open-plan offices, in order to attain appropriate acoustic comfort in open-plan offices. It can also be related to metrology, which today needs to be capable of accurately evaluating acoustic indicators that are of various complexities in spaces that are of non-uniform geometrical shapes or that are fitted out in non-uniform manner. Such progress may also be related to the computation models that are in widespread use, at the design stage or at the stage of correcting existing situations, for predicting expected noise levels (and their spectral or temporal characteristics) in any given open-plan office configuration. Finally, it may be related to the surveys necessary for understanding what employees feel about their workspace in general, and about their sound space in particular.

This paper proposes to take stock of all of these aspects, and to attempt to clarify some forward-looking points of view on what is needed for future research and studies into open-plan office acoustics.

2. REGULATIONS

Even though the employer "should reduce noise to the lowest reasonably possible level" (French Labour Code (*Code du Travail*), pre-2008 edition), assessment of the risks in open-plan offices shows that the levels of sound exposure are below the legally required thresholds for action, even in most very noisy call centres [2]. The first of the thresholds for action is set, for continuous noise, at an exposure level of 80 dB(A) for 8 hours of presence in the noise (European Council, directive 2003/10/EC). It is easy to understand that, in an open-plan office where the ambient noise rarely exceeds in the range 60 to 65 dB(A) on average, that level is never reached.

Noise is, however, the physical discomfort or annoyance that is most targeted in complaints from employees working in open-plan offices, well above thermal discomfort, lighting discomfort or other disturbance and annoyance factors related to the work environment. Regulations, whose thresholds are focused on damaging noise present in processing industries, therefore do not make relevant entry points for establishing target figures with a view to improving the sound situation for employees in open-plan offices.

Since then, standardisation has focused on analysing ambient sound in the tertiary sector or on setting targets to be reached for acoustic comfort, with indicators other than those described in the above paragraph.

3. STANDARDISATION

3.1. Ergonomics international and French standards

Ergonomics standards [3-4], applicable to the tertiary sector or to work done on computer screens, make it possible to determine to what extent employees subjected to a certain amount of ambient noise can be capable of doing their work while avoiding tiredness and fatigue, and in particular auditory fatigue, while reducing stress risks (noise being a co-factor) and while maintaining their performance levels (e.g. reducing risks of error). The texts refer to an average level $L_{Aeq,T}$ that it is recommended to keep below 55 dB(A). Even if those recommendations have the merit of going beyond the regulations, the limitations of such an overall appraisal are self-evident. An average level is a quantity that is simple, but that is also simplistic and extremely reductive, in which the temporal fluctuations and the spectral richness of the disturbing noise are omitted.

3.2. Acoustic international Standards

The only acoustic international standard specially dedicated to open-plan office is the ISO 3382-3: 2012 Acoustics —Measurement of room acoustic parameters— Part 3: Open plan offices [5]. This standard is a measurement one, published under the auspices of the Scandinavian countries. It is intended for furnished rooms with no people present during the measurement. This standard provides recommendation for the measurement of acoustical quantities such as the spatial decay rate of speech, $D_{2,S}$, the A-weighted sound pressure level of speech at a distance of 4 m, $L_{p,A,S,4m}$ or the distraction and privacy distances (respectively r_D, the distance from speaker where the STI – Speech Transmission Index - falls below 0.5 and r_P, the distance from speaker where the STI falls below 0.2). These indices can be used for comparing different solutions in design or acoustical treatment. Nevertheless, no target values are provided which could help to classify an open-plan office as good or bad in terms of acoustical conditions for the workers.

3.3. Acoustic French Standards

A few years ago, the French standards authority proposed its Standard NFS 31-080 [6], which addresses the acoustic performance of office spaces and considers the performance of an area of office space, often prior to it being fitted out, and therefore by looking at potential improvements during the design stage. That standard may be termed "architectural" because it focuses only on the *empty office* without its occupants, and it therefore does not take into account the occupancy noise (apart from the noise from fixtures such as ventilation equipment). However, it does have the merit of proposing an office typology (individual offices, communal offices, and ancillary spaces) and it classifies the various offices on the basis of their acoustic performance. That acoustic performance is estimated with the office being empty, but it is assumed to be directly related to the level of noise that might ultimately be evaluated in the occupied office. The performance is given relative to target values for quite conventional physical indicators (such as, among others, spatial decay of the sound levels, background noise of the equipment, reverberation time, and insulation from airborne noise), all these indicators being related to acoustic treatment and its capacity to insulate from the outside and to deaden the noise inside the premises.

The work that continued at French level [7] resulted in a draft called Pr NF S 31 199 (Acoustics – Open offices: programming, design and usage) that is supplementary to the above-mentioned architectural standard for:

- defining a new typology of open-plan offices, relative to the work activity conducted in them, and concentrating on the needs of communication between individuals in the space;
- looking at objective indicators of the acoustic quality of the room, and also at the possibility of communicating or of isolating oneself from the ambient noise;
- also looking at (and this is new) what the employees themselves feel about their sound environment, through a questionnaire.

It is clear that the developments in standards are going hand in hand with the developments observed in the thinking of stakeholders on the subject of sound discomfort in open-plan offices. In our opinion, these developments concern three notable aspects:

- firstly recognition and taking account of *speech and ambient noises* (specificity of the spectrum, unsteadiness, envelop modulations) as being the keystone of investigations into the acoustic quality of open-plan offices;
- then taking account of the occupants having *specific tasks* to accomplish and a *quality of communication* to uphold with colleagues or external contacts;
- finally, alongside all of the objective criteria familiar to the acoustician, taking account of what the occupant of the open-plan office *feels*, and thus of the subjective aspects (that are also sought to be linked to the objective criteria).

To summarise, we have thus reinforced the quantitative by the qualitative, as has been done in other fields of acoustics (transport noise, machinery noise: sound quality, sound design).

What further developments are expected? What will these standards that are in the pipeline or that have only just been deployed leave out? It is too early to say but it is certain that, beyond the recent developments, individual control, by each occupant of the open-plan office over their acoustic comfort will assuredly be an interesting challenge for the future.

4. NUMERICAL PREDICTIONS

The models used in the context of occupational noise or of architectural acoustics have, in recent years, become better suited to open-plan offices. In general, historically, they were designed to check that the design of a noisy workshop made it possible to shield workers from damaging noise [8], or to check that a single source (such as an orchestra) could content a whole audience distributed around a large concert hall, or to check that the acoustics of a building could correspond to regulations (for these two last topics, a simple research on internet can give access to a large choice of commercial software.)

In models for checking the design of workshops, the environment was generally of simple geometrical shape (shoebox-shaped workshop) and was initially extremely reverberant (the model then serving to propose improvement solutions), and, in such an environment, the field was often highly diffuse. Adapting the models to open-plan offices did not take place directly, since such offices have characteristics that differ considerably from those of the types of workshop for which the models were originally built. Firstly, the very large number of architectural details to be taken into account (desks, furniture, low dividers, etc.) made the model input descriptions complex (cf. Figure 1). Secondly, the computations themselves required higher complexity intrinsic to propagation in such premises, e.g. for taking diffraction into account [9].

As in the past, numerous computation models coexist today, some of which are accurate but limited, for example in terms of frequency, while others are more approximative but stick closer to the reality out in the field (complex geometrical shapes, and broad frequency band). It is plain to see that advantages and drawbacks, performance and limitations are shared on the various boundaries that each user might define for their own needs.

What should we expect of these models today? Many things are lacking, apparently, because the results are

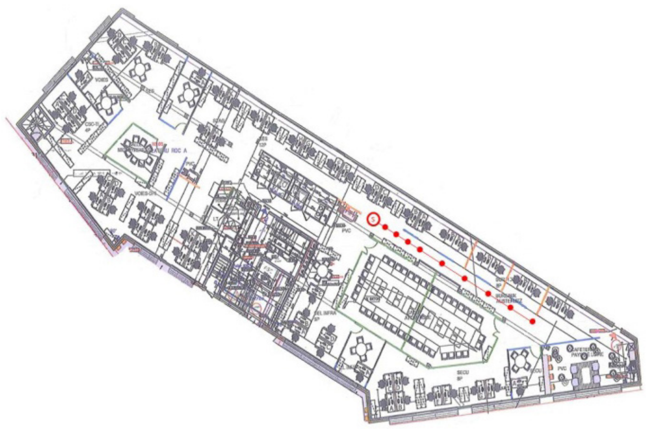

Figure 1. *example of the architectural complexity of an open-plan office (850 m², and 70 employees).*

still too often confined to overall mapping (as they were for industrial noise) or to estimates of spatial decay. The specificity of the open-plan office (with a large number of sources that can possibly be considered as directional, with unsteady noise, etc.) and the specificity of the associated indicators (intelligibility, discretion, etc.) are still not really in widespread use in the validated models.

Secondly, the designers are still awaiting models that are extremely simplified (rapid, capable of producing rough outlines) for roughing out situations as of the pre-project stages. Such models can be developed very advantageously and, of course, while validating them by means of more comprehensive models, and while being capable of linking them to acoustic performance indicators for rooms of various complexities. Finally, what would be novel would be to connect them to indicators related to the (subjective) discomfort felt by users.

5. METROLOGY

Although the models are very useful in the design and engineering phases or during correction of existing situations, a field approach and *in-situ* checking of situations or of attainment of objectives are still necessary. What metrology for measuring, what magnitudes is being asked for today for open-plan office acoustics?

5.1. Conventional indicators

Today, conventional indicators of pressure level are easily measurable with a sound level meter: $L_{Aeq,T}$ which is A-weighted equivalent sound pressure level; L_{50} which is A-weighted sound pressure level reached or exceeded for 50% of the measurement time with $L_{Aeq,1s}$; L_{max} which is the maximum value for $L_{Aeq,1s}$ over the measurement time; pressure per octave band. They can be measured with the room empty (NF S 31-080) or with the room occupied.

Although their limitations have been emphasised, the simplest indicators are naturally the ones that have been in widest use for a very long time, and, for an acoustician performing a sound diagnostic survey on an open-plan office, they represent the first figures from which observations and then recommendations will be derived.

Conventionally, the acoustic quality of the room is measured by means of other indicators requiring artificial sources of noise: RT_{60} which is reverberation time at –60 dB (impulsive source or interrupted continuous source); D_{L2} which is spatial decay, as measured along straight lines in the absence of furniture, with continuous sources of pink noise (NF S 31-080); insulation from exterior and interior airborne noise and from impact noise.

A recent development in the latter conventional indicators concerns spatial decay. Historically implemented in France, in noisy industrial premises (Order of 30 August 1990), it was measured along straight lines in corridors or gangways with pink noise sources and was therefore limited to 6 dB by doubling the distance (spherical waves in free space). Implementing it in furnished open-plan offices posed various problems: how to take account of the specificity of the large number of workstations (= noise sources) and of the way the workstations are laid out; how to take account of the specificity of the most disturbing and annoying noise in an open-plan office. It required a shift away from physics (–6 dB/doubling) and from the industrial spectrum to go further than Standard ISO 14257. Today, pursuant to International Standard ISO 3382-3, it is possible to trace decay through furniture (desks, screens, low dividers, etc.) to obtain a result of, for example, –8 dB/doubling of the distance. Furthermore, that standard recommends a source having a speech spectrum. That development makes it possible then to compute a sound pressure level at 4 m from the disturbing source, and, by measuring the background noise at the points of the decay, to compute the Speech Transmission Index (STI) or a discretion radius (STI < 0.5) in meters.

On the basis of these new recommendations, we thus have access to magnitudes that are closer to the reality of the open-plan office in which background noise is naturally more a conversation noise and for which workstation-to-workstation intelligibility is a magnitude to manage actively (in order to enable communications to take place or, on the contrary, to avoid disturbance and annoyance due to unnecessary understanding of unwanted and distracting conversations).

5.2. New indicators

The challenge today is to start by showing the utility of the conventional indicators related to speech intelligibility and to have them accepted. For example, STI is still not often measured by office acousticians in design offices and engineering consultancy firms. But the challenge is also to show that that indicator is insufficient for relating the background sound measured in open-plan offices to the sound discomfort felt by their occupants.

Intelligible speech signals in open-plan offices would appear to lead to higher disturbance in accomplishing a task [10]. An interesting characteristic of speech noise, relative to its intelligibility, would seem to be its rate of modulation. Listening "in the gaps" in modulated noise makes it possible to increase intelligibility, which is not measured by STI. It would therefore seem to be interesting to go further and, for example, to improve this indicator by modifying it to take account of modulation [11].

Furthermore, linking what the employees feel to acoustic indicators (levels, emergences, musical indicators, brightness, noisiness, roll-off, etc.) or psycho-acoustic indicators (loudness) capable of differentiating between different sources would enable progress to be made in characterising the ambient sound related to the discomfort [12-13].

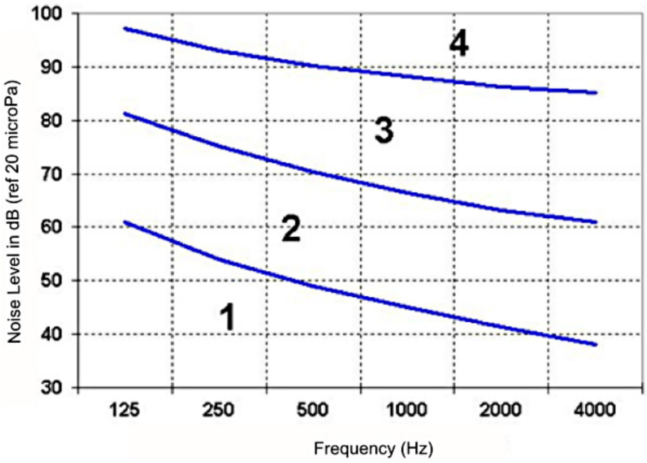

Figure 2. *"Wisner" curves [17].*

5.3. Noise perception

Noise perception in open-plan offices is of course a subjective factor which depends on many factors (health, stress, etc.) which affect each person differently. Nevertheless, some of these factors are independent of the subject and can be proved to be responsible for noise annoyance, discomfort and auditory fatigue. These factors are physical factors such as, for instance, noise level or noise level depend factors such as NR (Noise Rating) curves developed by the ISO in 1971 [14] or derivatives of them (Preferred Noise Criterion, PNC or Balanced Noise-Criterion, NCB [15] which have come to "Wisner" curves [16], well known and in widespread use in France by OSH specialists. They serve, in particular, to define, by frequency band, limits for ambient sounds that may are may not be bearable by tertiary-sector employees depending on the intellectual work that is required of them. Wisner curves, reproduced in Figure 1, set the following limits for ambient noise measured octave by octave from 125 Hz to 4000 Hz:

- in zone 1, intellectual work, even when complex and demanding a high level of concentration, can be done without any discomfort relative to the noise level;
- in zone 2, complex intellectual work can become difficult. Routine (administrative or commercial) work is not disturbed significantly;
- in zone 3, complex intellectual work is extremely difficult. Routine (administrative or commercial) work is difficult; and
- in zone 4, prolonged exposure can lead to deafness.

Generally speaking, what occupants of an open-plan office feel can be *measured* through surveys which are of great interest to the acoustician or to the designer of open-plan offices, whenever it is *linked* to *objective* measurements.

Here, we need to go beyond checking whether the noise is disturbing or annoying, to determine what type of noise it is, for what reasons, and for what consequences on the progress of the work on the tasks to be accomplished, and possibly what consequences ultimately on the health of the employees.

To that end, questionnaires can be filled in by the occupants of an open-plan office, with their anonymity being preserved, in the same way as other questionnaires have, for a long time, been used on noise (in the context of the environment: residents living close to noisy places, and transport users, for example) or on other issues relating to what employees feel about their own health, their stress, their well-being at work, etc.

A questionnaire satisfying these objectives has been produced in a research project [17] and used in tertiary-sector firms. Since 2013, it has been filled in by about 300 employees of 15 firms. It comprises about sixty questions grouped together into sections:

- type of respondent (sex, age, length of service, etc.);
- what is the physical environment of the workplace and what control over it and what satisfaction relative to it does the respondent have?
- what is the sound environment of the workplace and what discomfort (disturbance/annoyance) is felt?
- how sensitive to noise in general is the respondent?
- what does the respondent feel about their own health?

That questionnaire has already made it possible to segregate the various sources of noise into various categories related to the discomfort (intelligible speech, unintelligible speech, office machinery, and footsteps). Through all of the questions addressed, it makes it possible for advantageous use to be made of the discomfort feelings recorded with respect to other dimensions (e.g. age, or indeed sensitivity to noise or to stress, etc.).

Above all, the questionnaire has often been used concomitantly with objective measurements, which makes it possible to achieve the above-indicated objectives of attempting to link the indicators (conventional or more innovative) to the discomfort felt in the field.

Today, it is proposed that the questionnaire be an integral (informative) part of the above-mentioned standard NF 31 199.

6. CONCLUSION

It is clear that open-plan office acoustics will continue to be the subject of studies and research and developments in standards in the years to come, both because that mode of work organisation has a bright future, and also because we are in a field in which the acoustic levels, which are lower than in industry, are more conducive to qualitative and complex studies.

What can we hope for from developments in the various tools available to us for optimising the acoustics of these workplaces?

On the standardisation side, it would appear that a consensus has been reached on recognising the specificity of the noise and of its propagation in open-plan offices. Beyond that progress, design and engineering offices are sometimes a little reticent about seeing indicators and target values that they do not yet master appearing in standards. There are indeed problems of implementation (technical aspects) and of cost (commercial aspects) related to the services, and then the same obstacles can be encountered on the aspects relating to recommendations. It remains to hope that these difficulties will, in time, be overcome by means of tools (metrology, processing of questionnaire data, computations) made available to practitioners and by means of the progress in everyone's expertise. In any event, regulations will doubtless not come to the rescue of standardisation because, as we note above, our feeling is that the legislature already has its work cut out with addressing damaging levels of noise without making a legislation that is already complex more cumbersome by specifically addressing individual sectors like the tertiary sector or linking noise discomfort with other discomfort or other risks (stress). Furthermore, the current trend is to leave the social partners a lot of leeway so that they can adapt, on a case-by-case basis, specific recommendations on occupational discomfort and pollution through agreements at trade or sector level or at company level.

As regards numerical models, history shows that several philosophies continue to coexist, between those who want to go quickly and those who want accuracy, between mathematicians and practitioners, etc. We are not going to reconcile the divergences or differences here and we would then be tempted to reach an agreement at any cost, by talking about *compromise solutions*, which would be inelegant. In our opinion, these differences or divergences all have good reasons to exist and will thus be lasting. It would be positive to talk of complementarity rather than antagonism. There have already been numerous studies and pieces of research on these subjects over the last thirty years. It would appear that the progress expected today would lie more:

- in achieving a ratio of accuracy to description effort that is reasonable in view of the time allotted to studying a case for a consultant acoustician;
- in the possibility of adding criteria in relation to sound discomfort to models;
- in the possibility of linking recorded figures to criteria that are subjective or described in the standards.

For metrology, all of the most innovative tools exist, at least in the prototype state, in the laboratories. In order to go further, we need to validate protocols (e.g. measurement of L_{eqA}, STI) in an experimental context out in the field that incorporates constraints related to the work done in the open-plan offices: employees present, ambient noise measured with all of its components, fluctuations, etc. We also need to develop new indicators that should correlate with the perception of sound, and define the perceptive dimensions (discomfort, annoyance, decrease of performance, fatigue, etc.) that should be used for qualifying the effect of sound on workers in open spaces. These correlations should be based on laboratory subjective tests whose protocols have still to be defined.

The questionnaires used systematically in the offices on the employees, together with objective measurements, are, to the best of our knowledge, novel and original. They are fully justified by the aspects related to *perceived discomfort* or *discomfort felt* that we are seeking to highlight, and on which light is shed by the relatively low levels of noise in open-plan offices. According to the initial observations, they show results that are very interesting for steering the acoustician towards targeted analyses of situations, of noise sources, of laying-out or fitting-out configurations, or of acoustic treatment.

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