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A CASE STUDY OF LOW-FREQUENCY NOISE

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Abstract. *Sound waves below 20 Hz, which are generally inaudible to humans, are called infrasound. When infrasound and the less audible sound of the lowest frequencies (10 to 200Hz) appear as an element that disturbs people and is harmful to health, it is low-frequency noise (LFN). This air-borne noise has a much greater range than normal audible frequency sound and LFN travels much further on the ground. Stronger or longer-lasting infrasound around 7-20 Hz directly affects the human central nervous system and can cause disorientation, anxiety, panic, depression, nausea, discomfort, vomiting, etc. Sooner or later, the waves can lead to damage to the nervous and/or cardiovascular system. It is estimated that about 2.5% of the population may have a low-frequency threshold that is at least 12 dB more sensitive than the average threshold, which corresponds to almost 1,000,000 persons in the age group 50 to 59 years in the EU-15 countries. LFN is recognized as a particular environmental noise problem, especially for sensitive people in their homes. Conventional noise assessment methods are not suitable for LFN and lead to wrong conclusions and consequently to wrong decisions. An LFN source is more difficult to localize, difficult to suppress, and spreads rapidly in all directions so that it can be heard over great distances. All existing sound field visualization methods have a lower frequency limit of 125 HZ. Low-frequency waves surround the noise source and such a source is practically "undirected". In the paper, we described the LFN assessment carried out, which we identified in a commercial/residential building. The measurements were carried out in the immediate vicinity (3-4 km as the crow flies) of the object in question, at the site of industrial facilities (V1 and OM2), the pond complex, and the gas and transformer station. The LFN in the facility was initially unidentified, and the source search diagnostics were based on the method of comparing the generic spectral distributions of the LFN in the facility with other selected measurement positions.*

Key words: *low frequency noise, low frequency noise identification method*

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1. INTRODUCTION

Usually, we use the word sound to denote only the human-audible part of this wave with frequencies in the range between 20 Hz and 20,000 Hz. Sound waves below 20 oscillations per second, which are generally inaudible to humans, are called infrasound, also low-frequency sound (LFS). When infrasound and less audible sound of the lowest frequencies (10 to 200 Hz) appear as an element disturbing and harmful to human health, it is low-frequency noise (LFN). The greatest and most harmful effect on the brain is the sound frequency of 7-8 Hz. (Novak, 2021). In the LFN region, hollow structures in the body are affected: 5 Hz for the chest, 20 Hz for the head, and 80 Hz for the eye cavity.

About 2.5% of the population with a low-frequency threshold that is at least 12 dB more sensitive than the average threshold corresponds to almost 1,000,000 people in the 50-59 age group in the EU-15 countries. This is a group for whom low-frequency noise causes special problems. (Leventhal, 2004).

LFN spreads both by land and by air. LFN traveling through the air has a much greater range than the sound of normal audible frequencies, and LFN travels much further through the ground. Due to its long wavelengths, LFN is very penetrating and reaches large distances, even 5 kilometres.

Research has shown that the perception and effects of sounds at low frequencies are quite different compared to mid or high frequencies. The main reasons for these differences are as follows:

- weakening of the sense of pitch when the sound frequency falls below 60 Hz;
- detecting sounds such as pulsations and oscillations;
- a significantly faster increase in loudness and interference with increasing sound pressure levels at low frequencies than at medium or high frequencies;
- complaints related to a feeling of pressure in the ears;
- disturbances caused by secondary effects, such as the rattling of building elements, windows, and doors or the clinking of objects;
- lower sound transmission losses in buildings at low frequencies than at medium or high frequencies.

Evaluation procedures should be modified to evaluate sounds with a strong representation of low-frequency components (LFCs). The measurement site can be changed and the frequency evaluation is irrelevant because sound with strong low-frequency content causes greater disturbances than predicted by the A-weighted sound pressure level. (ISO 1996-1, 2011).

2. LONG-DISTANCE NOISE TRANSMISSION

The environment in which noise propagates is called the sound field, which includes the sound source, the propagation pathway and the receiver (emission, transmission and immission). For immission, we can take the equivalent level of sound pressure in the octave band at the receiving point in the direction of the wind (Wind Direction) L_{fT} (DW) is calculated for eight octave bands with a rated mean frequency from 63 Hz to 8 kHz according to the equation (1) (SIST ISO 9613-2, 2012):

$$L_{fT}(DW) = L_W + D_C - A \tag{1}$$

where

L_W is the sound power per octave band, in decibels, relative to the reference sound power 10^{-12} W (1 pW), D_C directivity correction, in decibels, describing the degree of deviation of the equivalent continuous level of the point source in a given direction relative to the level of the undirected point sound source radiating the sound power L_W; D_C is equal to the sum of the D_I directivity index, the point source, and the D_Ω index, which takes into account the propagation of sound to a spatial angle of less than 4π steradians; for an undirected point sound source radiating into unobstructed space, D_C = 0 dB. An attenuation in octave bands, in decibels, occurs during propagation from the point source to the receiver. The attenuation of A in equation (1) is given by equation (2):

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc} \quad (2)$$

In transmission, there is a sound attenuation effect caused by the following physical effects:

- geometric divergence, A_{div}
- atmospheric absorption, A_{atm}
- ground effect, A_{gr} sound attenuation due to soil effect (solid, porous or mixed soil)
- reflection from the surface, A_{bar} attenuation of sound due to obstacles
- sound attenuation due to various other effects of A_{misc}, e.g. obstacle diffraction: attenuation of sound when propagating through overgrowth, through industrial areas, and when propagating through built-up areas, (SIST ISO 9613-2, 2012).

2.1. Geometric divergence

The geometric divergence Adiv takes into account the spherical propagation from a point sound source in a free field; the corresponding attenuation in decibels is the same (Equation 3).

$$A_{div} = \left[20lg\left(\frac{r}{r_0}\right) + 11\right] dB \quad (3)$$

where d is the distance from the source to the receiver, in meters, d_0 is the reference distance (= 1 m)

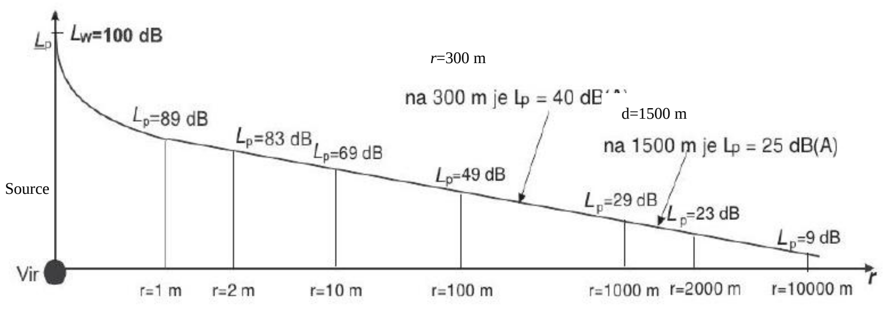

Fig. 1 Noise attenuation due to geometric divergence (Čudina, 2020)

2.2. Atmospheric absorption

The attenuation due to atmospheric absorption A_{atm}, in decibels, during the propagation of sound at a distance r in meters, is given by equation (4):

$$A_{atm} = \frac{\alpha r}{1000} \tag{4}$$

where α is the atmospheric attenuation coefficient of sound in the atmosphere, in decibels per kilometre, for each octave band at the mean frequency of the band (see Table 1). The coefficient of atmospheric attenuation in the atmosphere is highly dependent on the frequency of sound, ambient temperature and relative humidity, but significantly less on the ambient pressure. It is evident that at low frequencies, atmospheric dissipation up to 1000 is less than that at higher frequencies 8000 Hz.

Table 1 Coefficient of atmospheric attenuation of sound due to atmosphere α for octave noise bands (ISO 9613-2, 2012)

Tempera-ture ^{0}C	Relative Humidity %	Atmospheric attenuation coefficient α, dB/km							
		Nominal midband frequency, Hz							
		63	125	250	500	1000	2000	4000	8000
10	70	0.1	0.4	1.0	1.9	3.7	9.7	32.8	117
20	70	0.1	0.3	1.1	2.8	5.0	9.0	22.9	76.6
30	70	0.1	0.3	1.0	3.1	7.4	12.7	23.1	59.3
15	20	0.3	0.6	1.2	2.7	8.2	28.2	88.8	202
15	50	0.1	0.5	1.2	2.2	4.2	10.8	36.2	129
15	80	0.1	0.3	1.1	2.4	4.1	8.3	23.7	82.8

2.3. Amplification of low frequencies in rooms due to interference

The ripples of sound in an enclosed space excite modal frequencies, which are the resonant frequencies of a specific space. If the geometry of the room is square, and the dimensions of the room are comparable to the wavelength of sound, there may be marked fluctuations in sound pressure in it. Comparison of annoyances of different types of noise sources at otherwise equal levels of room noise and shorter wavelengths, such modes of oscillation are not pronounced, due to other effects, e.g. diffusion (Deželak, 2020).

Changes in indoor sound pressure levels can be significant, and in contrast to high frequencies, they exceed 20 dB. Also, the subjective sense of loudness, and especially its variations, are significantly greater at low frequencies than at high frequencies. For example, an increment of 5 dB at 30 Hz is equivalent to an increment of 10 dB at 1 kHz, depending on changes in the subjective sense of volume. So once a low-frequency sound is detected, it quickly becomes extremely unfavourable.

In closed spaces, there are different ways of sound fluctuation, which is the result of the formation of standing waves, which occur with the interference between incident and reflected sound waves from individual walls or various obstacles in the room. As a result, the noise level as a result of such a standing wave can be strongly dependent on the location in the room. Modes of such oscillation occur at certain frequencies called resonant frequencies (eigenfrequencies), in which the distance between individual amplitudes is determined by a multiple of the corresponding wavelength. The resonant frequencies f_0 of a square room can be calculated using equation (4) (Deželak, 2020):

$$f_0 = \frac{c_0}{2}\sqrt{(\frac{l}{L_x})^2 + (\frac{m}{L_y})^2 + (\frac{n}{L_z})^2} \quad (4)$$

where f_0 = frequency of natural oscillation Hz c_0 = speed of sound, l = mode of oscillation along the length of the room m = mode of oscillation over the width of the room n = mode of oscillation over the height of the room L_x, L_y, L_z = length, width and height of the room in meters (Larsen, 1972).

3 Noise Assessment with Strong LFCs Representation

LFN is recognized as a particular environmental noise problem and research has shown that A-weighted alone is not sufficient to evaluate sounds with characteristic tonality, impulsiveness, or a strong representation of low-frequency components. To estimate the long-term response of the community to sound disturbance with some of these specific characteristics, a decibel correction shall be added to the A-weighted sound exposure level or to the A-weighted equivalent continuous sound pressure level. Research has also shown that the sounds of different means of transportation or industrial noises elicit different community responses to a disturbance at an otherwise equal A-weighted equivalent continuous sound pressure level.

3.1. Basic Physical Indicators for Sound

In acoustics, there are several different physical indicators that describe sound expressed in decibels (e.g. sound pressure level, maximum sound pressure level, equivalent continuous sound pressure level). The levels corresponding to these physical indicators usually differ for the same type of sound. This often leads to confusion. It is therefore necessary to define basic physical quantities (e.g. sound pressure level, maximum sound pressure level, equivalent continuous sound pressure level). A - weighted is generally used to evaluate all sound sources, except for high-energy impulse sounds and sounds with a strong representation of low-frequency components. A - weighted should not be used to measure peak sound pressure and LFN.

4 Identification of Low-frequency Noise Using a Practical Example

We conducted an LFN assessment that disturbs residents in a commercial/residential building. Measurements were continued in the vicinity (3-4 km as the crow flies) from the object under consideration, where industrial facilities (Vand OM), a complex of ponds (P), a gas and transformer station are located. The LFN in the facility is unidentified, the source search diagnostics was based on the method of comparing the generic spectral distributions of the LFN in the facility with the other selected measurement positions described in Table 2.

Measurement equipment is used: Sound analyser, microphone and preamplifier and handheld acoustic calibrator: NTI AUDIO, XL2-TA. Handheld acoustic calibrator: Bruel & Kjaer 1256. Software used, data transfer: XL2 Projector PRO Display & Remote-Control Tool for the XL2 Sound Level Meter.

Table 2 Description of measuring positions 1 - 12.

Measuring position MP	Description of the measuring point
1.	Interior of the building at 9:00 p.m.
2.	Exterior of the facility at 9:15 p.m.
3.	Transformer station
4.	P (Peer ponds complex with a pump system)
5.	B
6.	In front of the V1 factory
7.	OM1
8.	OM2
9.	G
10.	Gas Plant
11.	J
12.	Interior of the building at 11:00 p.m.

Conventional noise assessment methods are based on A-weighted L_A sound, which greatly reduces the emphasis on low and high frequencies. A - weighted can lower the amplitude too much at low frequencies and their impact can be ignored too quickly. Many countries already have standards for the measurement and characterisation of low-frequency noise. An example of such a standard in Germany is DIN 45680: Measurement and evaluation of low-frequency environmental noise. The recommendation in the standard is that measurements should be made without weighting/evaluation. Table 3 therefore shows the measured unweighted/linear values of the L_z , Z- weighting sound pressure level (SPL) at 1/3 octaves (One-Third-Octave bands). These results are graphically illustrated in Figure 3.

Table 3 SPL as $L_{z\,max}$ in dB in the frequency interval from 6.3 Hz to 250 Hz

MP	6.3 Hz	8 Hz	10 Hz	12.5 Hz	16 Hz	20 Hz	25 Hz	40 Hz	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz	250 Hz
1	39.1	42.9	44.9	44.2	45.5	48.8	49.0	53.1	49.4	60.7	57.2	61.0	61.7	64.5	68.7	59.0
2	39.9	38.1	34.9	39.7	33.1	35.2	33.3	43.4	46.1	42.7	45.3	41.3	37.7	28.8	30.3	30.7
3	47.0	48.1	52.0	45.2	41.5	48.3	42.5	40.7	34.5	31.0	29.0	37.3	28.1	28.7	32.1	29.2
4	39.4	38.6	39.1	37.0	36.6	36.1	34.3	34.5	39.0	41.8	40.0	42.9	40.5	37.5	32.1	34.8
5	34.8	37.2	31.2	36.7	34.1	33.3	32.7	36.9	48.4	52.2	60.0	53.7	45.6	36.7	37.7	36.5
6	44.6	47.0	44.7	47.5	57.5	48.1	63.4	54.8	55.4	45.9	45.9	50.1	42.9	39.6	36.9	33.8
7	38.3	38.3	40.4	43.6	53.0	56.0	53.9	69.0	62.6	64.8	61.3	55.9	57.9	50.7	53.5	50.7
8	44.2	48.2	46.1	44.6	44.2	46.5	45.5	47.9	49.1	43.5	46.7	40.2	37.0	40.0	36.0	34.3
9	52.5	53.0	53.0	52.9	67.5	55.7	66.4	55.6	56.9	50.8	51.1	53.3	48.1	45.3	44.5	42.9
10	42.9	46.5	47.0	47.3	49.9	49.3	46.5	43.0	53.2	43.7	43.1	43.6	43.9	40.2	33.2	29.9
11	53.3	53.1	50.7	43.7	41.5	38.3	38.7	37.5	32.3	31.1	29.0	40.3	36.7	30.8	28.7	31.7
12	36.5	36.2	34.6	33.2	33.8	33.9	32.5	27.3	29.2	33.6	32.2	30.5	27.0	29.9	26.9	29.0

We were interested in whether LFN limit values were exceeded inside the building (Table 4). Graph 2 shows that they are vastly exceeded in the range of 40 Hz upwards (Figures 2 & 3).

Table 4 LFN limit values at night in accordance with DIN 45680

f (Hz)	10	12,5	16	20	25	31,5	40	50	63	80	100
L_z (dB)	95	86.5	79	71	63	55.5	48	40	33.5	33	33.5

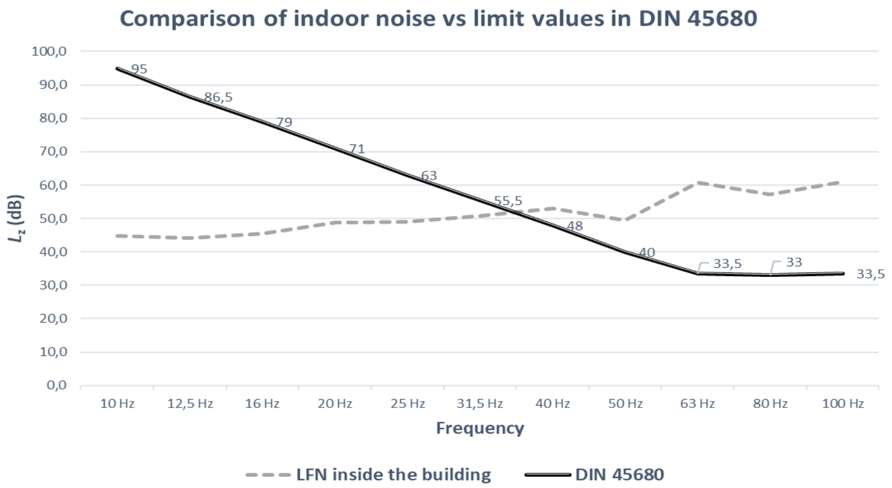

Fig. 2 Comparison of indoor noise with limit values in DIN 45 680.

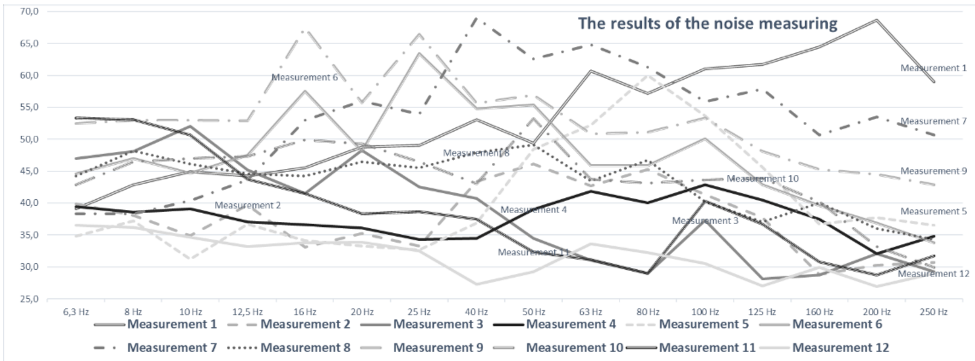

Fig. 3 LFH expressed as $L_{z\,max}$ at One-Third-Octave bands in the interval 6.3 – 250 Hz, all measurement positions 1 to 12.

4.1. Measurement results

Figures 4 – 9 compare the results of the measurements.

In Figure 4, the spectral distribution of LFN in the interior of the facility is measured at different times: at 9 p.m. and 11 p.m., as shown in Table 2. The frequency of 63 Hz stands out. The frequency of 200 Hz is the result of an event in the object itself, it is not present in the second measurement in the building.

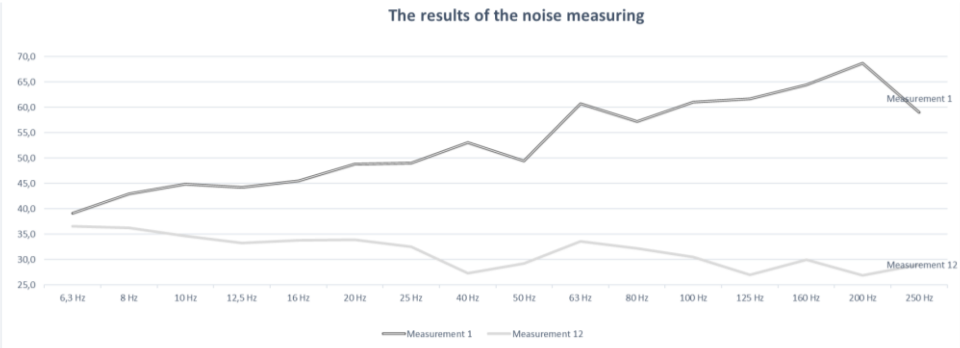

Fig. 4 Measurement 1 and 12 (Table 2). LFN expressed as $L_{\text{z max}}$ on One-Third-Octave bands in the interval 6.3 – 250 Hz, measurements made at different time intervals.

Figure 5 provides a graphical representation of the measurements 1, 2, 3 in 12 (see Table 2). Measurement 2 taken in front of the house itself shows the same generic spectrum as in the house itself. Measurement 3 in front of the transformer station shows a typical 100 Hz, which is not detected in the house. The transformer station can be ruled out as the dominant cause of LFN in the house.

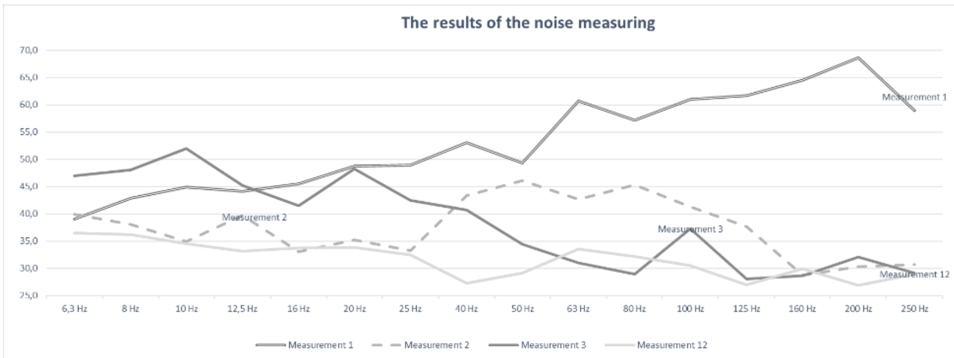

Fig. 5 Measurement 1, 2, 3 and 12 (Table 2). LFN is expressed as $L_{\text{z max}}$ on One-Third-Octave bands in the range of 6.3 – 250 Hz.

Figure 6 provides a graphical representation of the measurements 1, 4, 5 in 12 (see Table 2). Measurement 4 shows the same generic spectrum as in the house. It is necessary to investigate why this occurs, so what is the P (Peer -house connection? Measurement 5 before measurement point B shows 80 Hz, which is detected at measurement point O.

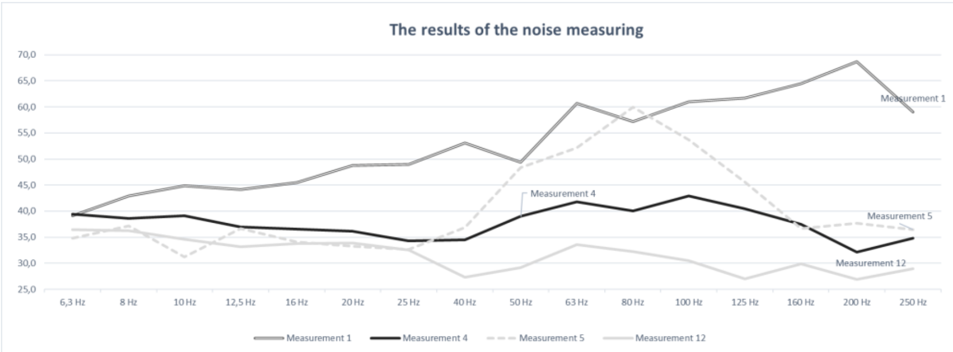

Fig 6. Measurement 1, 4, 5 and 12 (see Table 2). LFN is expressed as $L_{z\,max}$ at One-Third-Octave bands in the interval 6.3 – 250 Hz.

Figure 7 provides a graphical representation of the measurements 1, 6, 7 in 12 (see Table 2). Measurement 6 shows the expressed LFN at 16 and 25 Hz, which are not detected in the house itself. Measurement 7 shows a distinct 40 Hz, which is not typical of a house, so O can also be ruled out with a high degree of probability.

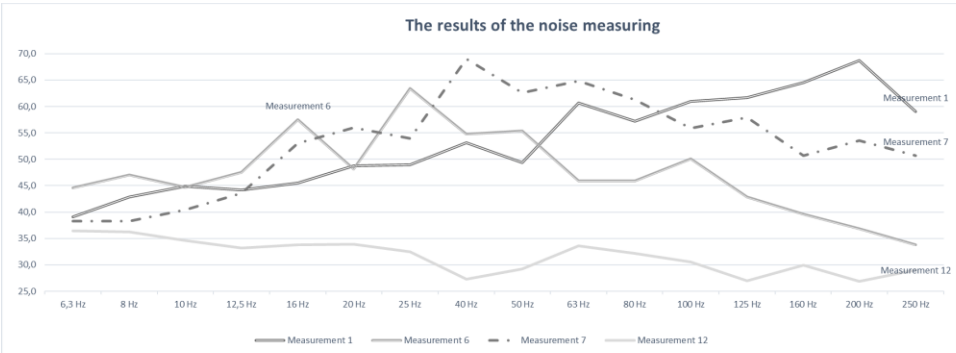

Fig. 7 Measurement 1, 6, 7 and 12 (see Table 2). LFN is expressed as $L_{z\,max}$ at One-Third-Octave bands in the range of 6.3 – 250 Hz.

Figure 8 provides a graphical representation of the measurements 1, 8, 9 in 12 (see Table 2). Measurement 8 shows LFN, which is not typical for the generic spectrum in the house! Measurement 9 shows prominent 16 and 25 Hz, which are not characteristic of the house, so V can also be ruled out.

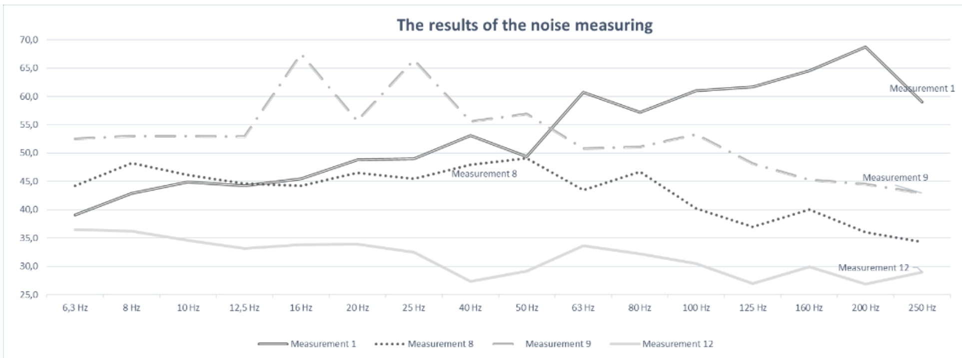

Fig. 8 Measurement 1, 8, 9 and 12 (see Table 2). LFN is expressed as $L_{\text{z max}}$ One-Third-Octave bands in the interval 6.3 – 250 Hz.

Figure 9 provides a graphical representation of the measurements 1, 10, 11 in 12 (see Table 2). Measurement 10 performed at the gas plant shows LFN, which is partially similar to the generic spectrum in the house in terms of the LFN P (Peer) form.

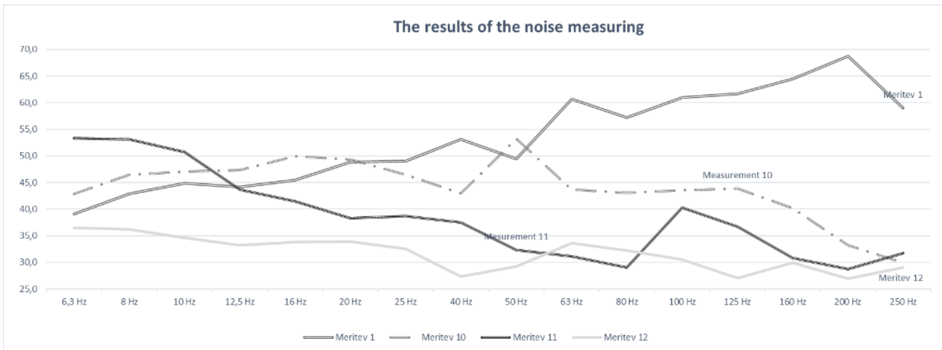

Fig. 9 Measurement 1, 10, 11 and 12 (see Table 2). LFN is expressed as $L_{\text{z max}}$ at One-Third-Octave bands in the range of 6.3 – 250 Hz.

4.2. Comment Measurements

The threshold of harmfulness of low-frequency noise is not sufficiently defined by the general noise determination and assessment procedure, which refers to certain relevant standards (A-weighted sound level). Since LFN is generally inaudible or poorly audible to humans, we considered it as a separate category of environmental pollution and looked at specific international standards such as DIN 45680 and ISO 7196.

On the basis of the measurements carried out, we excluded the transformer station and both industrial facilities as the cause of LFN in the facility in question and estimated that the pond system was in the first place and the gas station was a possible source in the second place.

5. CONCLUSION

Methods of describing, measuring, and estimating environmental noise are used to characterize LFN and are related to the human response to noise. The increase in LFN brings a number of adverse consequences to the environment, but the exact relationship between response and dose still remains a subject of scientific debate. In addition, it is important that all the methods used are practically feasible in the social, economic, and political environment in which they are used. For these reasons, there is a very wide range of different methods currently used around the world for different types of noise, which causes great problems for international comparison and understanding. If we analyse the recommendations for conducting LFN measurements, we can highlight the following facts:

- The usable frequency range is from about 5 Hz to about 100 Hz. In the range below about 20 Hz, some countries use G-weighted to evaluate sound. Above about 15 Hz, several countries use Octave or One-Third-Octave bands analysis in the range of about 16 Hz to 100 Hz. (G-weighted is specified in ISO 7196).
- States with special procedures for assessing LFN do not use A- weighted in the same way that it is used to evaluate medium and high-frequency sound. LFN is only rated in a limited frequency range as noted above.
- A number of states have set criteria for LFN based on indoor sound measurements rather than outdoors. Others use indoor and outdoor measurements in their national standards.
- One of the questions in estimating LFN is whether room resonances at low frequencies can create conditions that are difficult to predict based on outdoor measurements. This can be especially important when evaluating specific dwellings. However, outdoor measurements may be sufficient to estimate the prevalence of severe disturbance in the population environment.
- LFN-induced rusting in building elements is an important factor in the disruption it causes. The methods in Appendix B of ISO 1996-1 specifically take into account the factor of this roaring associated with high-energy pulsed sound. Some countries have set indoor criteria for continuous sound, which include both audible sound and roaring sound. Others have established separate boundaries for enclosed spaces when assessing sound-induced buzzing.

In this paper, we described the LFN assessment that we identified in the commercial/residential facility. Measurements were carried out up to 3-4 km as the crow flies from the object under consideration, on the site of industrial facilities, pond complexes, gas and transformer stations. The cause of LFN in the facility was initially unidentified, but the source search diagnostics was based on the method of comparing the generic spectral distributions (Z – weighting) of LFN inside and outside the facility with other selected measurement positions. Based on the analysis shown, the actual source of LFN is recognized with a high degree of probability.

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