



Low-frequency noise: a biophysical phenomenon

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Abstract

Complaints on low-frequency noise were till recently fairly unexplained, but audiological research shed light on the mechanisms that enable perception of frequencies below the threshold of average normal hearing. It was shown that exposure to low-frequency sound may alter the inner ear. This results in an increase of sensitivity to low-frequency sounds, and as a result, previously imperceptible sounds becomes audible to the exposed person. Interactions between inner-ear responses to low and higher frequencies furthermore account for perception of low-frequency sound, as well as the property of the hearing system to perceive so-called difference tones.

Introduction

A growing minority of people experiences an increased sensitivity for low-frequency sound. Not surprisingly, they complain about noise, even about loud noise in some cases. Their complaints about the presence of hum, buzz, and rumble are often not recognized as a nuisance, since the majority of people does not perceive the very low frequencies. Low-frequency noise (LFN) may have serious health effects like vertigo, disturbed sleep, stress, hypertension, and heart rhythm disorders [1].

The number of sufferers is growing, and this has two possible causes. The sources of low-frequency sounds increased in volume and dimension over the past decades, and auditory sensitisation takes years to develop.

Nowadays, the main source of low-frequency noise is the public infrastructure: wind turbines, gas transmission grid, industrial plants, road and railway traffic, sewerage, and so on. Their expansion is enormous as it keeps pace with our rapidly increasing welfare and industrialization. Recent inventions like district heating (citywide hot water pipeline grids for home warming and hot tap water) and underground waste transportation furthermore add on to the sources of LFN.

In recent years, more insight has been gained into the biophysical explanation for sensitisation of the hearing system for low sound frequencies. This paper discusses several of the proposed mechanisms for this biophysical phenomenon.

Biophysics of low-frequency sound perceptibility

Sound audible to the human ear is in the frequency range 20 -20.000 Hz, and the ends of this spectrum are barely audible. In audiology, the measured range is restricted to the frequencies relevant to speech 125 - 8000 Hz [2]. LFN may be loosely defined as having frequencies below this range.

Sounds of all frequencies can also be transmitted via the skull, thus by-passing the eardrum. This is called bone conduction and it occurs most with low frequencies. Tones with low frequencies therefore contain no spatial information for our hearing system. (For this reason stereo equipment has only one subwoofer.)

The maximum amount of sound pressure that is bearable is 140 dB (ref. 20 μ Pa), the threshold of pain. As illustration: heavy traffic generates about 80 dB, and a normal conversation 60 dB [2]. At average sound pressure levels, frequencies within the range of speech are better perceived than very low or very high frequencies with the same sound-pressure level. This is what the widely used dBA-weighting standard refers to. Figure 3 shows the low-frequency part of this standard.

The cochlea is a bony structure, with three fluid-filled compartments that are separated by membranes. The basilar membrane is set into motion by sound-pressure waves in the upper compartment. This excites the outer hair cells of the sense organ on the basilar membrane, the organ of Corti. This organ lies in the middle compartment of the cochlea. The outer hair cells act as pre-amplifiers, and they excite the inner hair cells. The inner hairs cells transduce the mechanical activity

into electrical stimuli to the brain. In Figure 2 the sensitivity curves of the inner and the outer hair cells are shown, along with the noise spectrum of a Dutch wind turbine. It is seen that noise above 50 Hz can be heard by the average normal hearing person. Noise below 5 Hz is not audible for anyone. The region in between is not audible, unless the sensitivity of a persons outer hairs cells are altered.

Frequency sensitivity of the cochlea is distributed over the basilar membrane from high frequencies at the basis (i.e. where the sound-pressure waves enter the upper compartment) to low frequencies at the apex (end point). At the apex, the cochlear upper compartment is connected with the lower compartment through a passage called the helicotrema. The pressure waves pass through the helicotrema into the lower compartment, in order to dispose of their remaining energy and extinguish.

Frequencies lower than about 20 Hz cannot be heard by the average person, but they can be sensed as vibrations, as most people will have experienced when standing near e.g. a subwoofer. A minority of people, however, are able to *hear* these frequencies as well. Low-frequency audiograms of three very sensitive persons are shown in Figure 1. These three subjects show to be able to hear sounds below about 20 Hz, sounds with pressure levels more than 20 dB less than the hearing threshold for normal-hearing persons. Several mechanisms in the cochlea may be responsible for this increased sensitivity and for other health effects. We will describe two hydromechanical mechanisms and two neural mechanisms.

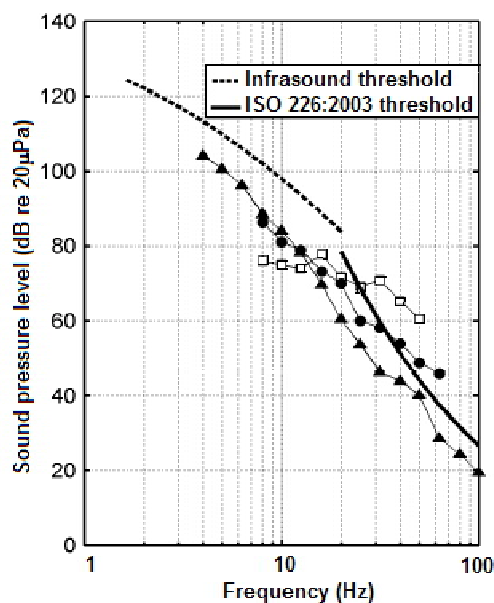


Figure 1: Hearing thresholds of three especially sensitive persons (from [5]).

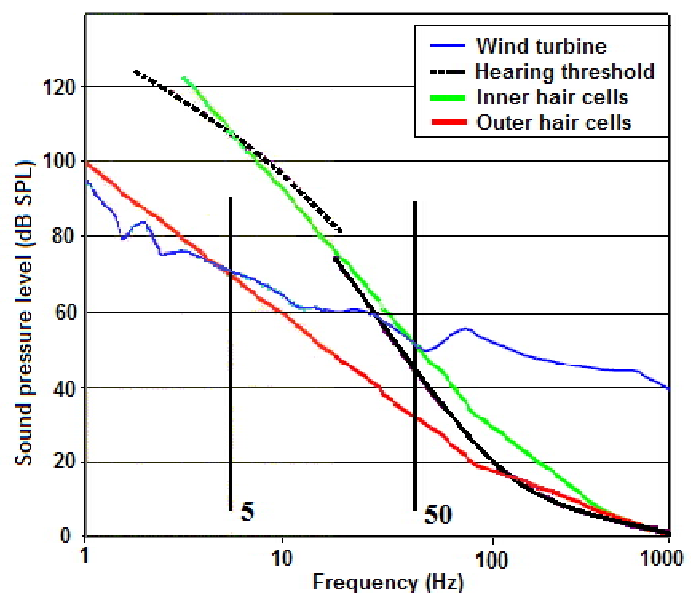


Figure 2: Unweighted noise spectrum of a Dutch wind turbine [7], hearing thresholds from Figure 1, and sensitivity curves of inner and outer hair cells [6]. The latter are based on animal hair-cell response characteristics, but with helicotrema and middle-ear characteristics for the human.

Stimulation of the cochlea has been shown to result in swelling (hydrops) of the middle-compartment fluid (endolymph) [3]. The swelling results in flow of endolymph through a narrow duct that is connected with the sacculus. The sacculus is a compliant chamber with sensory cells that generate neural impulses to the brain when the head makes movements. When these cells are excited due to the endolymphatic flow, this is experienced as vertigo (dizziness) [4].

Endolymphatic hydrops is also known to contribute to occlusion of the helicotrema. When the helicotrema is blocked, the pressure waves bounce at the helicotrema and travel back through the upper compartment. They interfere with incoming waves and, with that, intensify the pressure waves in the upper compartment. The returning waves start at the apex and will lose their energy along their way to the basis. As they have most energy near the apex, they will excite the cochlear area near the

apex most: and this is the area with sensitivity for low frequencies. This may make the ear 20 to 30 dB more sensitive to low-frequency sounds [8]. The distance between the sensitivity curves of the inner and the outer hair cells is indeed about 20 dB; this supports the idea of LFN-induced sensitivity enhancement.

As we saw from the dBA curve, higher frequencies are better perceived than low frequencies, at most sound pressure levels. However, at sound-pressure levels higher than about 85 dB SPL, the opposite was seen to occur: in measurements on the cochlear response of laboratory animals, the low-frequency part of the cochlea then showed more response to 5 and 50 Hz tones than to a 500 Hz tone [9].

Another interesting finding in this laboratory experiment is the observation of biological amplitude modulation: sounds with higher frequencies could suppress the response of the cochlea to very low frequencies.

With low frequencies at pressure levels that do not yield cochlear response (and thus no nuisance), a remarkable observation was made. A tone of e.g. 50 Hz could still exert its influence: it was able to suppress the response of the cochlea to higher frequencies [9].

When the spectrum of a noise source contains two *coherent* higher-frequency tones with only slightly different frequencies, their interference pattern show a beat with low frequency. Our hearing system perceives this form of amplitude modulation as a so-called difference tone. Normal-hearing persons can, under certain circumstances, hear this form of low-frequency sound too, e.g. when tuning a musical instrument. Musicians know these tones as ‘Tartini tones’. Readers unfamiliar with this biophysical phenomenon are invited to listen to a sound example that we present online [10].

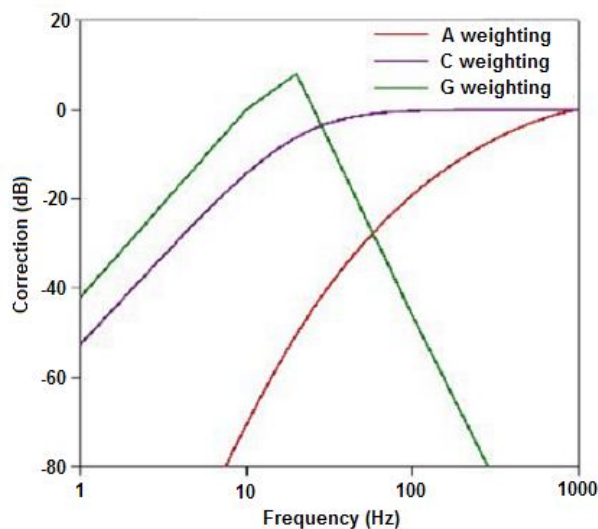


Figure 3: Equal-perception level curves used for weighting spectra, according to three standards.

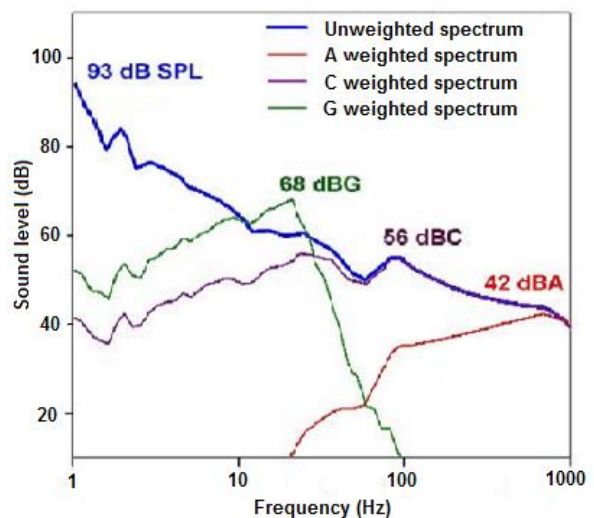


Figure 4: Wind turbine spectrum of Figure 2, with four different weightings.

Discussion and recommendations

Legislatory control of noise necessarily rests on noise-level standards for the average person, as these standards cover the majority of people. The ear of the average person is generally assumed to have a frequency-sensitivity characteristic according to the dBA-standard. When this standard is applied in the assessment of noise, as a weighting, the amount of low-frequency noise produced by public infrastructure seems small. The unweighted low-frequency level, however, can be considerable. For wind-turbine noise, this is shown in Figure 4.

A growing number of people suffers from LFN-induced enhanced hearing sensitivity for low frequencies, with enhancements of 20 dB or more. The experiments discussed in this paper furthermore showed that low frequencies can generate more cochlear response than higher frequencies, when



their sound-pressure levels are considerable. At the time of construction of the dBA standard, high-powered low-frequency noise was not as common as today. It is likely that the phenomenon of reversal of sensitivity was not taken into account in the construction of the dBA curve. Therefore, for assessing low-frequency noise, other standards than dBA are required. The dBC-standard might be considered for this purpose, or the more recent dBG standard. The dBG weighting is an ISO-standard and is especially designed for assessing low-frequency sounds [12], [13]. For a comparison, see Figure 4.

The elder generation has been exposed longest to the noise of public infrastructure. It was found that the prevalence of LFN-complaints increases with age [1]. This supports the conclusion that long-lasting exposure to low-frequency noise, inaudible for years to the exposed persons, may at the long term result in alteration of the cochlea; such alterations could already be demonstrated in laboratory animals.

When sensitisation finally occurs, the LFN “suddenly” becomes audible to the exposed person. This person will try and search for recent changes in his immediate surroundings that can be pointed to as “the” cause of his LFN problem. But not necessarily recent and nearby changes are the main and only cause. Ground-borne vibrations have a propagation length of tens of kilometres. In a small and densely built-on country as the Netherlands, the large propagation length inevitably causes the noise from the different numerous elements of the infrastructure to interfere and accumulate. So, looking for one unique structure as the source of nuisance may often be impossible and illogical. This explains why engineering attempts to localize “the” noise source are often fruitless. A single subset of infrastructure may in itself not produce sufficient low-frequency sound to cause problems, their combination may. In regulatory debates on combatting LFN, the discussion should therefore not focus on finding “the” industrial culprit (like “wind turbines”), but rather on the relative contribution of each industry.

A special type of interference is the difference tone that appears when two sine waves are coherent and close in frequency. This tone is not present as an individual frequency in the sound spectrum. In order to detect the presence of low-frequency difference tones, measuring power spectra does not suffice. Coherence should be detected and therefore the time-evolution of phase spectra should be studied. This should be done at an appropriate frequency resolution. Sound spectra are often presented with logarithmically-spaced frequencies, because this is in accordance with the frequency-discrimination characteristic of the ear. However, low-frequency beats arise from pairs of tones that are usually not distinguishable for the ear. To detect the presence of difference tones, spectral information with a high frequency resolution has to be gathered. The sufferer can indicate what beat period he hears, and this may serve as a guide to determine the in-situ required frequency resolution.

If low frequencies are actually present in the spectrum, they do not necessarily have to be audible, or even be continually present, to be perceived. This paradoxical fact was shown in the experiments, and is a property of the cochlea. When a low-frequency sound does not yield any cochlear response (and therefore no nuisance), it could still suppress the response to sounds with higher frequencies. In case the inaudible low-frequency sound shows up in intervals, the higher frequencies will seem modulated in amplitude. This may give rise to a perceptible beat with a period of the intervals mentioned.

Low-frequency sound may cause endolymphatic hydrops, which may result in vertigo. We assume that physiological process as lymphatic flow and helicotrema blockage cannot resolve as quickly as sound can be turned off. Therefore, the dizziness may persist after the low-frequency sound vanished. As a consequence, LFN-measurement may yield zero result while the sufferer still has the physical complaint.

Higher frequencies were found able to suppress cochlear response to low-frequency sounds. This form of masking may be an advantage for the LFN sufferer when there is a continuous presence of higher frequencies in the ambient noise. However, when high-frequency sounds show up in intervals, the amplitudes of the low-frequency sounds are modulated with the same period. Then, we



expect, another low-frequency beat will be perceived, with a period equal to the modulation interval.

The above three effects are all due to cochlear properties, but they cannot be solely ascribed to cochlear problems: they still require the presence of low-frequency sound in order to manifest themselves.

Data on the prevalence of LFN in the Netherlands do not exist. Systematic investigations have not yet taken place. The need to do so has become fairly apparent, but suitable measurement protocols still need to be developed.

In addition, a dedicated nuisance-assessment methodology needs to be developed for LFN. This is because LFN-sufferers miss many of the coping strategies that sufferers from traditional noise have. First, they do not have any means of shielding against LFN. Since LFN propagation is mainly structure-borne, closing doors and windows is not effective. Earplugs are of no use, because LFN bypasses the eardrum. Secondly, LFN has no spatiality and is therefore perceived as being located “within the head”. The sufferer literally cannot distance himself from the unwanted sound. Thirdly, LFN never lets up, since public infrastructure is continuously in operation. Fourthly, social control, like talking to the neighbours in case of music nuisance, is not applicable. Lastly, moving house will not bring a solution since the propagation depth of structure-borne low-frequency vibrations is large and the public infrastructure densely present in our small country. All this implies that LFN exceeds tolerable noise levels and noise durations sooner than traditional noise does under comparable (but not yet established) noise loads.

Acknowledgement

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