The text below is a translation of an article published in Dutch, in the trade journal "Geluid" (Sound). Journal Geluid aims at provinding administrators, officials, architects, urban planners, officials at companies, health care workers and other professionally interested parties with information about backgrounds, intentions and results of prevention and control of noise pollution, and noise and effects of sound in homes and at work. Reference: "M. Oud. Verklaring voor hinder van laagfrequent geluid - Biofysische benadering. (Explanation for suffering from low-frequency sound - Biophysical approach.) Tijdschrift Geluid, Kluwer Media, Alphen aan den Rijn, maart 2013". URL: http://tiny.cc/201303GeluidENG Translated by: the author.

Explanation for suffering from low-frequency sound

Biophysical approach

Recent research in the U.S. explains why more and more people perceive low sound-frequencies. Also in Netherlands, low-frequency sound causes problems.

By: Dr. Mireille Oud

About the Author:
Physicist Dr. M. Oud (Linkedin.com/in/MireilleOud) has a PhD in atomic physics, studied medicine for a limited period, and works as a scientist on signal processing and pattern recognition applied biomedical sounds, since 1995.

Being able to hear móre as you are aging, rather than less? This seems like a dream, but to whom it happens, it's a nightmare. Suddenly hearing more low sound-frequencies is very annoying. This is because such frequencies don't contain any information: in speech and music they are not present, and we cannot use them for directional hearing. And it's especially the latter, that makes them so annoying: due to the lack of spatiality, low frequencies seem to be localised 'inside' the head. Some people hear a soft hum, others a rumble as if there is a truck running in front of their house. Do they really sound? How is that possible? Why is the number of people who complain on low-frequency noise constantly increasing? And, how do we quantify the extent of this social problem?

REALLY HEARD

Sufferers can often indicate exactly where they can hear the annoying hum. The most trouble they experience in enclosed spaces such as homes and cars. Within these spaces, the spots with extra loud sound appear to be periodically in space. Great surprise about your predictional talents will be yours when you can point to the next loud spot. This amazement and the location specificity already form a quite objective evidence that the sufferer indeed perceives noise from the outside. It this just a matter of a resonance effect? In the house of such a sufferer, a municipal service did extensive research. Nothing was found.

To determine perceptibility, the above mentioned municipal service used a non-official sound threshold[a] that was compiled by TNO[b] from literature data on 55-year-old.[1] The values of this curve are somewhat higher than those of the official ISO curve that was measured in young, normally-hearing persons.[2] That causes the service to consider higher sound levels as 'inaudible' then officially should.
Biological parameters have considerable variability and medicine uses worldwide two standard deviations to determine what value is 'normal'. In this case, that means that almost 48% of the population has a threshold of up to 10 dB lower than the threshold curve (Figure 1).[3] The well over 2% of normally-hearing people with an even lower threshold have 'hard luck': they are wrongly considered abnormal. In our country, often a margin of only 6 ½ dB is used, which is slightly more than one standard deviation, and this standard allows up to 10% of the population to have 'hard luck'. In other words, 10% of the normally-hearing people can hear sounds that are officially reported as inaudible sounds. The home of the aforementioned sufferer did not exceed the threshold according to the 'Dutch standard '. According to the ISO 2%-standard, an audible tone that can cause a standing wave would well be present.

PHYSICS BETWEEN THE EARS

Nuisance Act is based on average people and hence accepts that a small number of people is faced with nuisance. But that small number is ever growing today: complaints about low-frequency noise are increasing worldwide. Symptoms are similar all over the world, only their degree varies. Some people complain of a soft hum, others of roaring noise. There seems to be something the matter. A combination of increasing machine power and increased sensitivity to noise seems to explain the increase in nuisance complaints. What has been built in the past decades for our infrastructure, mobility and industry, both underground and on top, is gigantic. The second, the increased sensitivity, might of course be psychological of nature, but it appears that it may also be biophysical. Neurobiologist Professor Salt of the Washington University shows this in his studies.

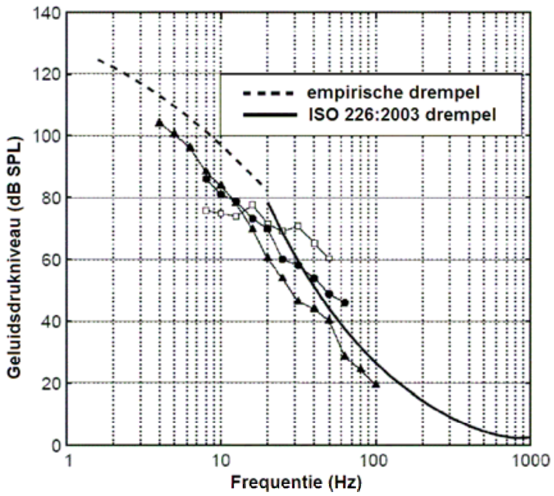

Figure 1: Hearing threshold and sample audiograms for low tones (SPL Ref. 20 micro-pa).[3] Explanation in frame 2 on page 9.

Prolonged exposure to low-frequency vibrations, he argues, can affect our inner ear (Figure 2). Irritation of the cochlea (a "snail-shell" shaped feature, Figure 3) by low tones can induce swelling of a part of it. Vertigo may result, a complaint we indeed hear with people affected by low-frequency noise. To quickly simulate such noise-induced swelling, Salt exposed laboratory animals to a tone of 200 Hz at 115 dB SPL. After just three minutes he could observe the beginning of swelling.[4] Swelling can also cause the passage between the upper and lower channel of the cochlea to narrow or get blocked. This also was imitated by Salt, by injecting a plug of gel in the passage. The blockade appears to induce larger pressure differences in the cochlea, in particular for low-frequency pressure waves. This makes the ear 20 to 30 dB more sensitive, especially for low-frequency sounds.[5] Such ear perceives a soft hum as noise. Literally.

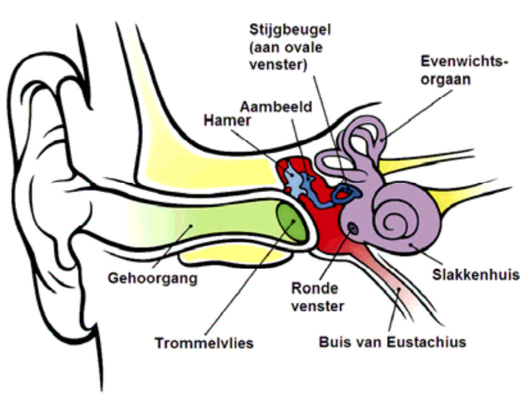

Figure 2: outer ear (white and green parts), middle ear (red part) and inner (lilac part). Explanation in frame 1 on page 9.

Yet, test engineers do not always see the disturbing hum show up at their sound meters. Then, the conclusion of their principals is often that the low tone is created in the head of the sufferer and 'therefore' not caused by the outside world. Is this true or false? It is true ánd false. If in the outside world two nearly identical tones sound, our ears may hear a third frequency that does not appear on the display of the sound level meter: the difference tone, a beat with a very low frequency (Figure 4). This "ghost sound" is a well known phenomenon among musicians, but is sometimes overlooked in the measurement world. Sufferers may perceive another kind of sounds that's not reflected in the measured spectrum. "Tinnitus", sound experts then easily say, to the annoyance of many of the sufferers. True or false? Again, both. Tinnitus, ringing in the ears, can also be caused by excessive stimulation of the ear with low-frequency vibrations. Some auditory nerve cells, the outer hair cells, then send electrical signals to the brains. In a normal situation, these cells function only as mechanical preamplifiers they do not generate sound perception.[6]

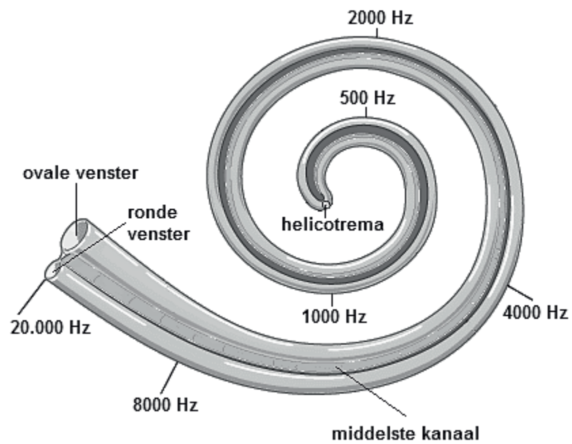

Figure 3: Cochlea. Explanation in frame 1 on page 9.

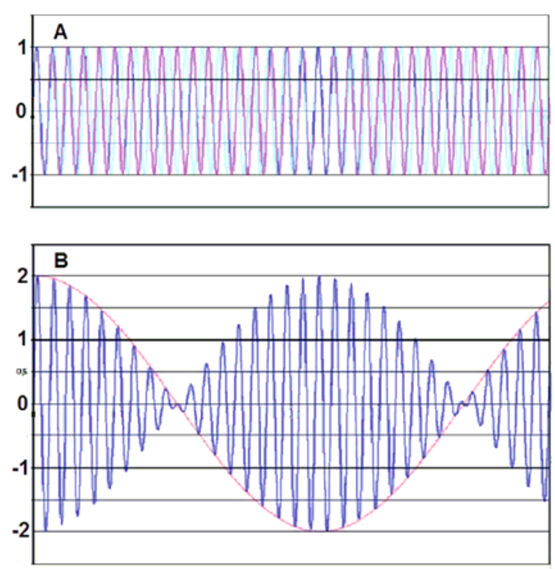

Figure 4: a. Two pure tones with almost equal frequencies (blue and purple lines). b. Interference of the two tones from panel a (blue line), and its envelope, the difference tone or beat (red line). Explanation in frame 3 on page 9.

Excessive stimulation of the preamplifier cells, the outer hair cells, can also give a feeling of pressure on the ears. Indeed, part of the sufferers say they cannot hear the low-frequency noise but they can feel it. Figure 5 shows how this comes about: it happens if the low-frequency sound stimulates the outer but not the inner hair cells. Then, one perceives something, but hears nothing.[6]

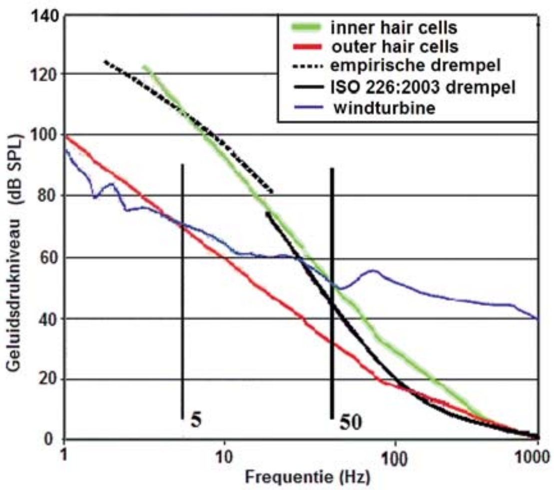

Figure 5: Sensitivity curves of auditory nerves (red and green lines),[9] hearing thresholds (black lines) and spectrum of Dutch wind turbine[11] (blue line). Pressures in SPL ref. 20 micro-Pa. Explanation in frame 2 on page 9.

Frame 1: Operation of the ear
The vibrations of the tympanic membrane (Figure 2) are transmitted by three tiny bones in the middle ear (ossicles) to the fluid in the cochlea. The cochlea (Figure 3) is a bony structure with three channels. The vibrations enter the upper channel at the oval window, pass a passage (the helicotrema) at the end of the channel, and propagate in the lower channel. The resulting pressure differences between the upper and the lower channel set the membranes surrounding the centre channel into motion. This movement stimulates the outer hair cells located in the middle channel, and the outer hair cells stimulate electromechanically the inner hair cells. The latter then send impulses to the brain. The cochlea functions, lengthwise, as a series of filters: near the oval window for high frequencies, and near the helicotrema for low frequencies. The cochlea is also connected to the vestibular system. In case of excess liquid in the middle channel, such as with Meniere's disease, one experiences dizziness.[8]

ABOUT THE THRESHOLD

Continuous exposure to low-frequency sound appears to harmful in the long run. Low-frequency noise is currently mainly found with middle-aged people, and this is the rationale behind the use of the informal hearing threshold curve that is based on 55-year-olds. However, the harmful effects of continuous exposure to low-frequency noise starts at an early age, so, before one notices any symptoms in oneself. It is therefore not a good idea to use as perceptibility criterion a hearing threshold curve for 55-year-olds.
The biophysical insights shed new light on the evaluation of this issue. The inability to objectify the global increase in the number of complaints may have the following causes:

Frame 2: sensitivity of the ear
The ossicles dampen with 6 dB/octave the sound that hits the eardrum. The helicotrema (Figure 3) dampens the fluid pressure wave that passes through it with the same order. The combination of these two transmission models of the human auditory system yields the noise sensitivity of the outer hair cells (red curve in Figure 5).[9] The electromechanical transmission of the fluid vibration from the outer to the inner hair cells also has a 6 dB/octave attenuation; this was measured in laboratory animals. The measured transmission is combined with the two transmission models of the human ear, and this results in the calculated noise sensitivity of the inner hair cells (green curve in Figure 5). Sound that results in stimulation of the inner hair cells, is heard.[9]. The hearing-threshold curves (black curves in Figure 5) indeed coincide with the green curve.

The ISO-standardized hearing threshold starts at 20 Hz. For lower frequencies, an empirical threshold was constructed from measurements from England, Sweden, Denmark and Japan.[3, 10] The spread of two standard deviations amounts to approximately 10 dB, a realistic magnitude illustrated by audiograms of three persons (two from Japan and one from Denmark), in Figure 1. To assess the extent to which we can hear ambient noise, recorded sound is usually dBA weighted. The dBA curve is, roughly, the inverse of the ISO hearing-threshold. If we extrapolate, by eye, the ISO curve to lower frequencies, we see that this curve (and thus also the dBA curve) significantly underestimates the hearing sensitivity: the empirical threshold clearly lies below. In line with this, the empirical curve is much less steep: -12 dB/octave. For lower frequencies, below 20 Hz, the dBG curve exists, since 1995.[7] The reciprocal of the dBG curve is, roughly, the hearing-threshold curve. The dBG weighting curve has a slope of 12 dB/octave, which indeed corresponds with the slope of the empirical hearing threshold.

- Over the years, the total sound pressure of low tones in our environment has become increasingly higher. Due to this, this sound exceeds with increasingly more healthy-of-hearing people their individual, normal perception-threshold.
-Prolonged overstimulation by, at first inaudible, low-frequency noise can reduce the hearing threshold by as much as 20 to 30 dB, making it audible.
-Ambient noise with low tones is present still more continuously. Once damaged, the ear will have no chance to recover, due to which it remains vulnerable and keeps giving complaints in periods with less noise.
-The sources of low-frequency noise are present in still increasing geographical density. For a sensitized person, it no longer helps to move (such as for living and work), due to which he experiences more nuisance than an equally sensitive person would have before.
-The sound pressure in our environment is underestimated by the threshold curve, if the usual margin of two standard deviations is not applied.
-Threshold curves do not take into account that our

auditory neurons already respond to sound before it has an audible level.
-Extrapolation of the dBA weighting curve for frequencies in the area below 20 Hz underestimates the actual sensitivity of our ear in that area (see Figure 5).

Frame 3: Perceiving what sound pressure spectra do not show

An example of an infrastructure element which is subject to much discussion in the scope of low-frequency noise, a wind turbine, is shown in Figure 5. If the outer hair cells are stimulated and the inner hair cells are not, still signals may be sent to the brain. One sees that, wind turbine sound noise, this effect occurs between 5 and 50 Hz.

If two pure tones with almost equal frequencies interfere with each other (Panel A in Figure 4), then we see and hear a beat (red line in Panel B). For a sound demonstration of this phenomenon, see slide 10 of: http://tiny.cc/LFG2012NAG. Musicians call such beats Tartini tones, and exploit them to tune their instruments. A trained ear recognizes such a low tone as a beat, but the naive listener may experience it as a real tone. With church organs, one takes advantages of this interference phenomenon to generate very low tones without having to build the long organ pipes that would actually be needed to make such low tones.

TO MEASURE IS NOT TO KNOW

Regulators prefer to send a technician with a sound meter, a standard, and the command to detect the source of pollution. With the current geographic density of sources, and the kilometre-long propagation of the low frequencies, however, the sound of different sources overlaps easily, and therefore "the" source can often not be pointed out. Difference tones cannot be easily seen in a spectrum, and cochlear defects by low-tones strain can not be seen at all in it. Therefore, the current form of noise measurements cannot completely map out the noise problem. A demographic survey in combination with the right statistics seems more appropriate at this moment : how many people experience what kind of noise, on which locations and at what times? What is their age, since when do they notice this noise, and to what extent? What sources are in which density spread over the area, how big is their increase over the years and per geographic unit? There may appear interesting correlations between these parameters, correlations that can offer a handle for further investigations. Examine relationship with sound-level measurements in the environment would of course also be interesting, but such measurements are only useful if carried out on many locations and times simultaneously (this is because interferences play a role, and because the source powers fluctuate considerably over time) and that would make them very expensive.
But if there is going to be measured, one golden rule should apply: always record and save the raw sound data, and only then carry out arithmetical operations. Raw sound data, that is, the digitized, dBL-calibrated, sound waves. Weightings, such as dBA and the possibly more appropriate dBG,[7] and spectral computation, like power spectra, can be performed next. This approach is important because weightings are still under discussion and because, for example, from power spectra no existence of difference tones can be derived. When the raw data stored, new insights can be applied retroactively.

IN CONCLUSION

People who attribute their complaints of discomfort to low-frequency noise, are often being disagreed with, because the presence of low-tones nuisance cannot always be determined objectively. That latter is because, on the one hand, their sound pressure is underestimated by an inappropriate sound weighting, and on the other hand, because that these tones may be entirely absent, as with the phenomenon of difference tones. Nonetheless, sufferers appear to be right in many ways. Prolonged exposure to low-frequency noise may possibly adversely affect the structure and operation of our hearing organ. Tinnitus and dizzy spells may be the results. The adverse influence may also lead to a reduced hearing threshold, making inaudible sounds audible or even perceived as loud. Globally, the number of people with this type of complaints increases. This is perhaps due to the ever stronger, continuer and more widespread prevalence are of low-frequency noise in our environment, as a result of the progressing development of industry, infrastructure and mobility.

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Remarks added to translated text:
[a] Applied in The Netherlands only
[b] TNO: Netherlands Organisation for Applied Scientific Research, tno.nl