# LOW FREQUENCY HEARING THRESHOLD IN RELATION TO PREDICTABILITY

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**Summary**

Low frequency hearing tests are uncommon, and for people that suffer low frequency noise disturbance often unavailable. Source detection of low frequency noise (lfn) is seldom straightforward and can therefore be costly. A developed semi-mobile low frequency hearing test should answer in an early stage if people that suffer low frequency noise can indeed hear the noise that is detected. After fabrication and installation of a large speaker and attenuator set for such tests, the set (Modorunai) was tested by performing audiological tests. Satisfied with the first results we introduced fading signals to see if these could be better detected because they can be more easily distinguished from blood circulation noise. Sufferers of lfn also mention thumping noise in their description of the suffered sounds. The results show that this type of noise significantly reduces the hearing threshold.

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## 1. Introduction

In low frequency noise disturbance, official measurements often find typical low sound pressure levels in places where this type of noise disturbance is suffered. Because of the physics of low frequency noise, a noise source detection is more challenging and can be costly or even ineffective. Some people suffer from auto-generated noise, e.g. tinnitus. Tinnitus is most common for high frequency tones, but some victims may suffer low frequency auto-generated noise. If so, more accurate measurements on the presence and distribution of a low frequency sound source have no added value.

If self-generated noise is the essence of the problem, not only can efforts be saved, but also guidance for victims to deal with such signals can be started earlier.

In the Netherlands such hearing test programs are sometimes available, but availability is highly dependent on funding and coincidence with other programs. Alara-Lukagro is a company that produces noise and vibration control systems, which has its own small test facility available for more than six months a year. Therefore the company was requested to make its facility available. However the background noise levels were not satisfying the maximum intensity in the 50 Hz 1/3$^{rd}$ octave band.

Because some victims also claim that their sensitivity is different for each ear, Alara-Lukagro decided to create a portable attenuator, which includes an internal subwoofer.

After quantifying several properties of the attenuators, low frequency hearing tests were conducted.

Because the inner ear has different mechanics than a microphone, low frequency pulses may propagate as a more audible tone in the inner ear. Not-steady noise has more impact. Impulsive noise is judged to be up to 10-18 dB more annoying [5]. Low frequency noise with 'rising levels' is punished with 5 dB [5]. Therefore this setup was also used to make a comparison between pure tones and fading tones.

## 2. Properties of the system and environment

The background noise levels in the test facility were measured before the design of the attenuators, the sound pressure levels were measured form 16:30 till 20:30 when activities around the facility were low. The results are shown in figure 1.

The sound pressure level around 50 Hz is higher than acceptable for background noise. The initial aim was to stay well below 10 dB(A) for each 1/3$^{rd}$ octave band in 90% of the time (L90). From the high difference between the time averaged sound pressure level $L_{eq}$ and the statistic sound pressure level L90 in the low frequencies can be concluded that short events contribute highly to the equivalent low frequency background level.


figure 1. background noise levels

The attenuators need to filter well in especially the 50 Hz 1/3$^{rd}$ octave band. Ideally the 50 Hz shouldn't rise above 0 dB(A) in L90 for both attenuators.
Both attenuators are different. One attenuator was designed to have a high noise attenuation, through a small hole and an attenuator design. The other attenuator houses a speaker and attenuates through absorbing planes in the middle of a reverberant area. The diameter is limited because the ear has only limited height difference with the shoulders of the test subject, see figure 2.

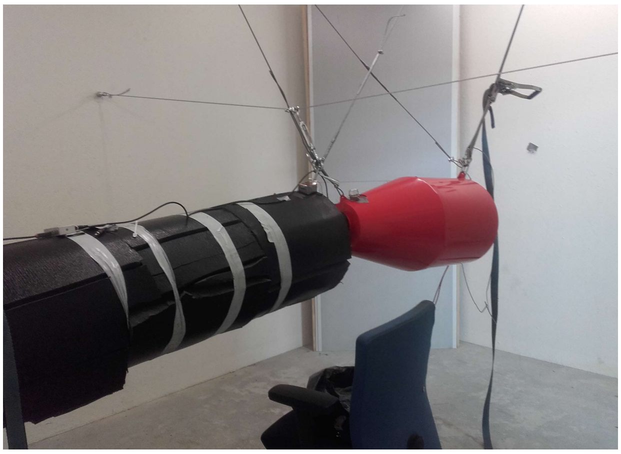

figure 2. Modorunai test setup

The attenuation values, which predict the difference between the background noise, and the noise going into an ear, were tested with the use of an artificial ear. The attenuation values were mainly limited by flanking noise. Therefore the area around the ear of the attenuator was equipped with a gel package. This resulted in better attenuation in the 50 Hz, see figure 3.

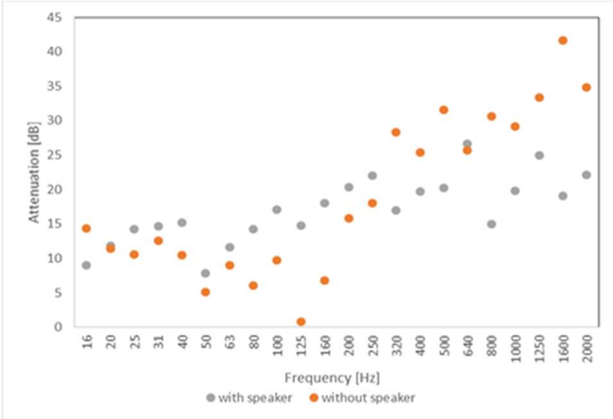


figure 3. effective attenuation levels

When the results of figure 1 & 3 are combined the acoustic contribution of background noise in the ear can be forecasted during the test (see figure 4). The values in figure 4 do not include blood generated noise and other human disturbances.

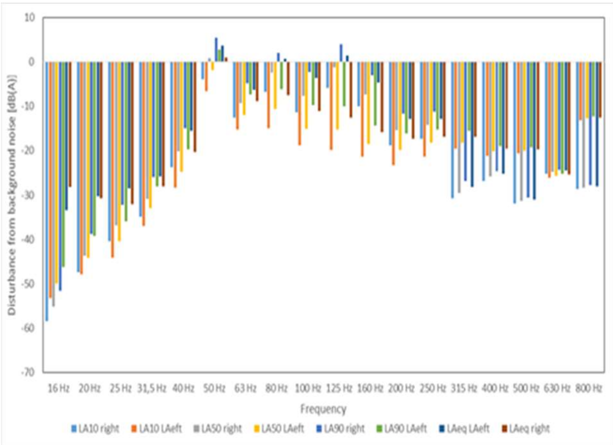


figure 4. expected background noise during tests

## 3. Blood generated noise conditions

The conditions predicted in figure 4 are better than most anechoic rooms. However blood generated noise within the 'modular dose relation units for noise assessment on individuals' (Modorunai) has more reflections than in an anechoic room. Therefore a statistic analysis of blood generated noise sound power levels was conducted, using microelectromechanical systems (MEMS) microphones within Modorunai and a headphone set. The MEMS differed only between 0 and 2 dB for each 1/3$^{rd}$ octave band with a B&K 2250 calibrated measurement device. The results are shown in figure 5.

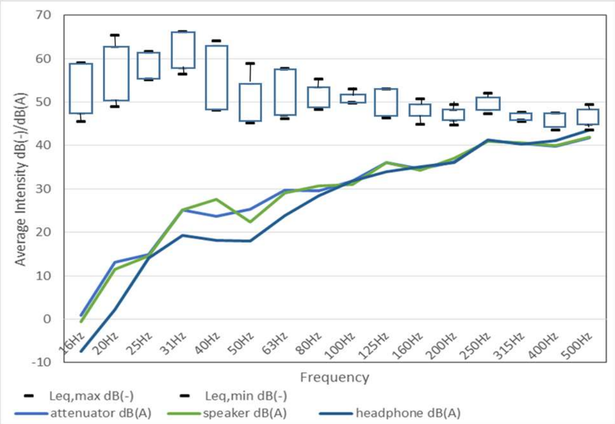


figure 5. blood generated noise

The average levels were determined using a low sample frequency. Note that average noise levels can be highly influenced when the subject moves even a fraction of the time, or when aliasing influences specific frequencies. The experiment should be repeated using a higher sample frequency. However the values around 25 Hz and 30 Hz show there is much more acoustic energy in these frequencies present which is not easily generated by movement of the volunteers. Therefore it is safe to assume these values are blood generated noise. This was also found on indicative more reliable experiments. The amount of blood generated background noise will not help the recognition of low frequency noise. This is consistent with lower sensitivity for lower frequencies than for higher frequencies where the energy content of blood generated noise is less.
The difference can be quantified by using room acoustics, or a different simplified model based on geometry. Blood generated noise sound pressure levels are respectively 5.5 and 7.2 dB higher in this setup for all frequencies than in a fully anechoic chamber. For the frequencies up till 100 Hz a slightly lower blood generate noise level was measured using a regular high quality headphone, Sennheiser HD 280 pro. The light material of the headphone was also tested for attenuation properties and proved no positive attenuation below 250 Hz. Leakage through the headphone is more beneficial in the very low frequencies than the gap in the attenuators, intended to bleed off excessive noise. Because of the negligible attenuation and the reflections in the mid frequency range above 125 Hz there is still more audible unwanted noise in the headphones than in the Modorunai.
When tests are conducted in an anechoic room, signal processing and generation equipment also produce noise. In the here reported tests all the equipment was in the adjacent room, and cables went through two attenuators. It is hard to say which test conditions have the least amount of background noise.

## 4. Audiological test

The first tests were fully conducted on 9 volunteers. From this data an average hearing threshold can be determined. The test persons were 7 male, 2 female, and 8 under 50, of which 5 under 25, and one over 80 years old. No test subjects that are included in this study had any history with hearing issues in the tested ear. The results are shown in figure 7.
The test persons were continuously fed with a low frequency pure tone. The intensity was shortly increased to help the subject recognize the tone. Thereafter the level was deceased until inaudible, and increased with 5-10 dB till a certain level and decreased again. This was repeated until the individual hearing threshold was found, then the sound level was kept 1 dB below this threshold, in order to check if the subject was unable to detect it. All tones where kept for a minimum of 15 s at a certain level. The intensity of the signal was kept 1 dB under the audible level for 1 minute in order to check the conclusion.
Interestingly figure 7 shows a discontinuity: 80 Hz proved easier to detect than either 63 or 100 Hz. More interestingly the average hearing threshold was significantly lower than the hearing threshold according to ISO standards [8]. A small attribution may be the age of our subjects, and the time provided to recognize the sound. The low average threshold is a good indication that this test method and conditions can be used, and results are accurate.

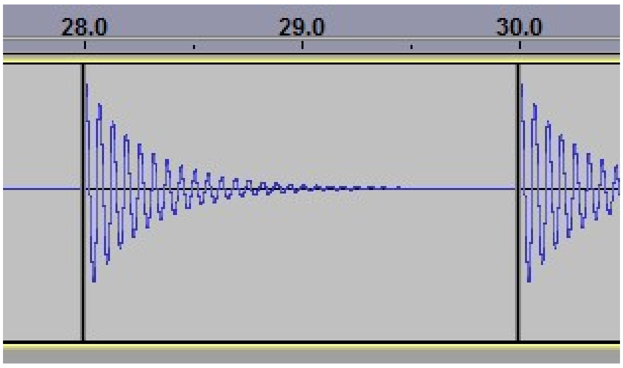


figure 6 test results pure tones, relative amplitude over time in seconds

A downside of this method is the length of the test. An experienced tester can significantly reduce the time of a single test till 15-20 minutes if executed when background noise is low.

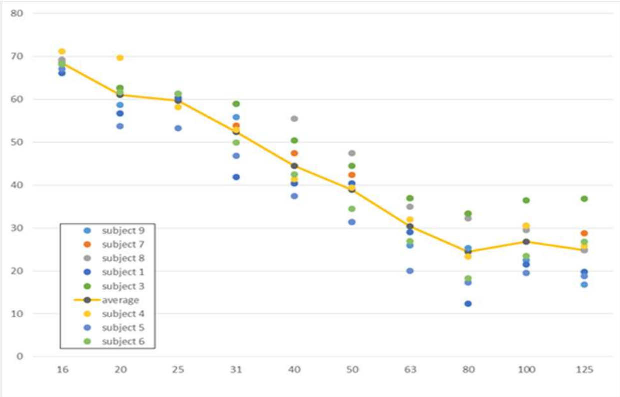


figure 7. hearing thresholds

Validation in MEMS near the subject ears in this research showed that the electronic signal was inadequate in order to predict intensities, and the response differed per frequency.

The accuracy of the MEMS is high, however it is more convenient and reliable to use the electronic signal as a reference. Therefore a conversion was introduced relating the electronic amplitude to the sound pressure levels on the ear, produced by the speaker. This conversion also incorporates the effects of the Modorunai.

## 5. Tones and fading tones

Not all noise suffered can be represented by pure tones. Sounds that are specifically disturbing are impact sounds. The noise of impact sounds can be best represented by an impulse response curve. Inspired by the impulse response curve, a fading tone was produced in order to test for comparison. A two seconds signal was faded from 100 till 3% acoustic energy content and repeated. The test method was the same as for pure tones. The signal is kept running and again the intensity is changed until a consistent positive recognition is found. The intensity is kept constant for a minimum of 10 seconds.

By repeating the signal every 2 seconds, the subject was able to count and check if the audible noise corresponded with their own hart rate. The sudden increase of amplitude till a 33 times higher amplitude sine shape every two seconds, see figure 6, may cause higher harmonic signals to dominate the audible noise. Therefore the relative electronic signal frequency content was analysed and compared using the fast Fourier transformation method of Hamming, see figure 8. Other methods may show different results.

In the electronic signal dispersion, see figure 8, the area of interest is the purity of the faded noise. In other words the relative intensity in the excited 1/3$^{rd}$ octave band compared to other octave bands. The fading signal is represented by the orange line. The intensity of the fading tone drops approximately 11 dB for each octave band. Knowing each octave band holds twice as many frequencies, the total sound power drop per octave band is 8 dB. This is less than the sensitivity increases per octave band, according to ISO [1]. Because of the intensity held by the peak, the intensity drop in the first octave band already is 24 dB, see the 31 Hz value in figure 9. Because the peak, seen in figure 8, is also about 22 dB higher than a straight line through 100 Hz. Which makes it unlikely that higher harmonic noises are more audible.

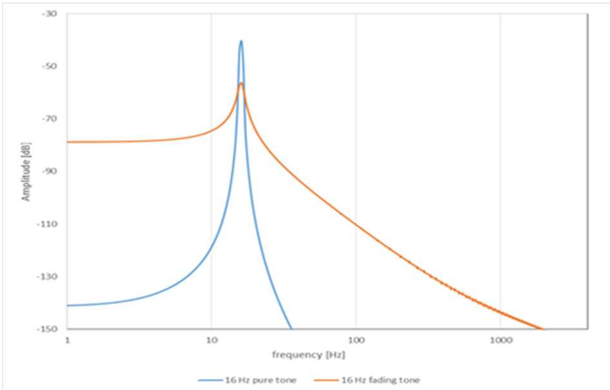


figure 8 intensity dispersion of pure and fading tone

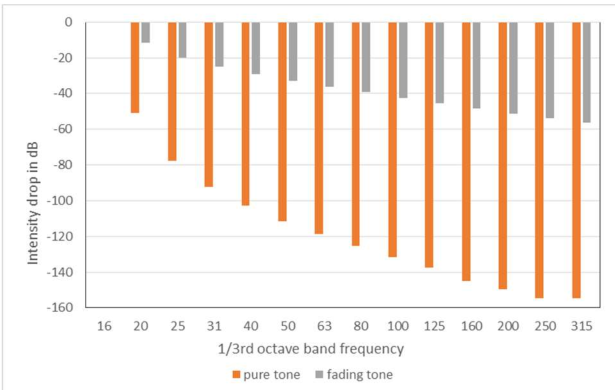


figure 9 intensity drop per 1/3$^{rd}$ octave band

In a follow up it would be advisory to optimize the sharp edges at the start of the higher intensity in such a way that much less higher frequencies are generated in the test signal. So it is certain higher harmonic sounds are not the cause of the audibility. The results of the hearing threshold for both the fading pure tone as the continuous pure tone are shown in figure 10. In the low frequencies the subjects were on average over 10 dB more sensitive to fading tones as for continuous tones.

This is especially interesting since the hearing threshold in the low frequencies was already lower than reported hearing thresholds.

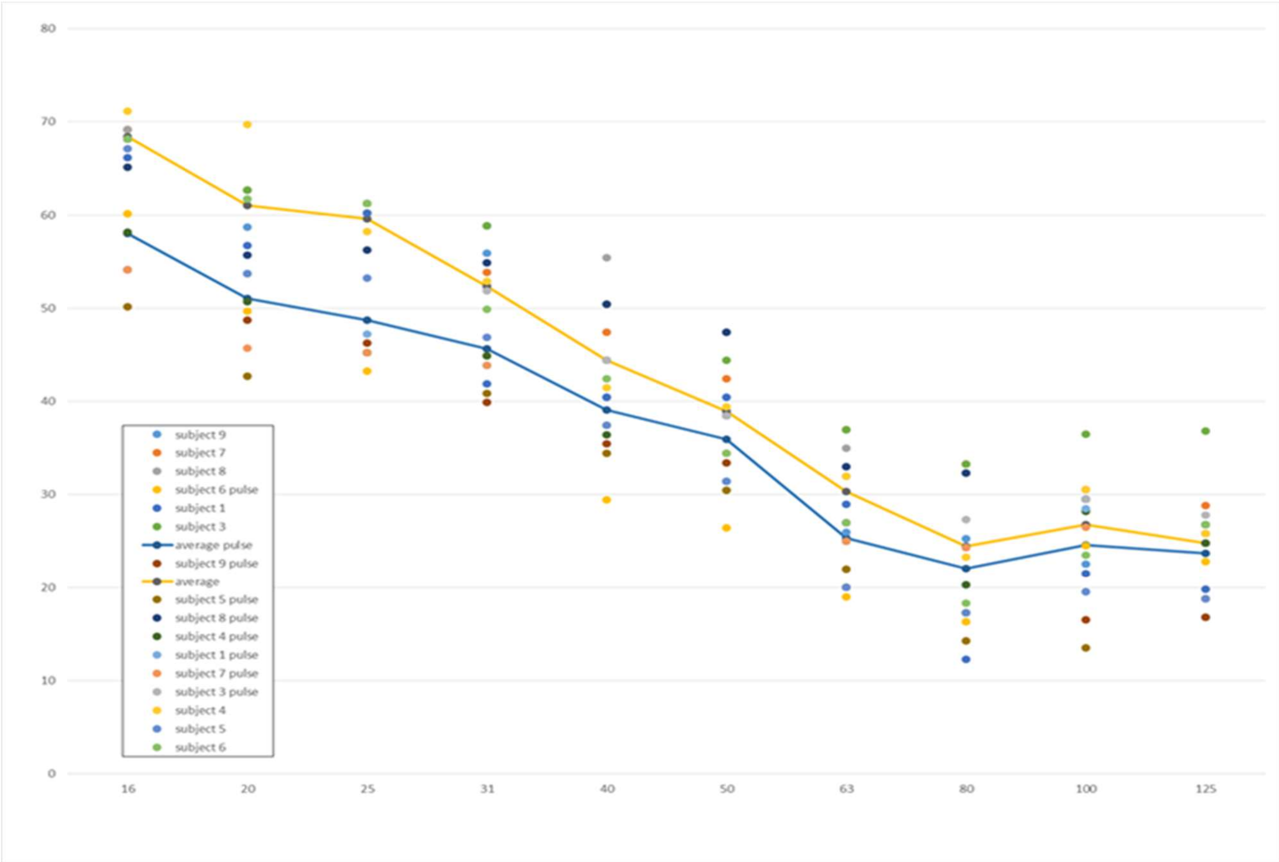


figure 10 hearing thresholds for (fading) tones

## 6. Different noise studies

In figure 11 the average curves of figure 8 are compared to the hearing threshold stated by ISO [8] and some legislation curves for the protection against low frequency noise across Europe [5], which are more stringent in the lower frequencies.

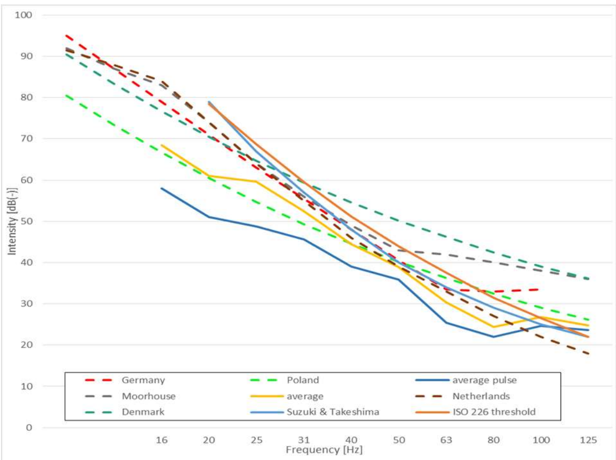


figure 11 comparison with documented thresholds [7,8] and legal boundaries [5,9,10]

The results are somewhat similar to both the extreme proposed regulation in Poland [3], being the same as the 10 dB(A) curve, and Suzuki & Takeshima [7]. The average threshold in 100 and 125 Hz is similar to ISO [8]. Most astonishingly the hearing threshold for 20 Hz for fading tones is 28 dB lower than ISO [8].

Consequently the hearing threshold for pure tones cannot predict whether or not measured low frequency noise intensities are audible. The time dependent behavior of the sound is an important aspect that can change audibility by 12 dB on average and even more for individual subjects. An audiological test is useful, but should at least include low frequency noise with similar time dependent character as the suspected noise complaints.

A spectral analysis of the suffered noise may not predict whether this specific sound can be assumed audible or not. The hearing threshold for sounds differs per individual. Moreover, because the audibility for low frequency fading tones is much higher than for pure tones, the average hearing threshold is significantly lower than can be found in literature.

This doesn't mean that legislation should be more stringent. When the disturbing sound levels are compared to earlier publications on the hearing threshold, the conclusion was drawn that audible low frequency sounds are by definition disturbing. When the audibility of low frequency sounds turns out to start at lower levels this conclusion can no longer be drawn. In the Rotterdam area a more stringent regulation for low frequency noise is already adopted [4,6], and correlates well with the level of disturbance. However there will and should always be a relation between the average hearing threshold and legislation.
Before conclusively can be said if a sound is audible by a specific individual, the audibility should be tested with time dependent test signals that correspond with the suffered noise disturbance.

## 7. Conclusions and recommendations

From this study, it must be concluded that the sensitivity for low frequency noise shouldn't only be tested using pure tones. The human hearing is much more sensitive for low frequency noise than we have assumed up till now. Fading Low frequency tones till about 80 Hz are about 10 dB more easily detected than pure tones. The baseline hearing threshold on our test subjects was much lower than in most literature. More research is necessary in order to determine the real human hearing threshold, and to develop different hypothesis about the reason for the difference in sensitivity.
Because pure tones are seldom representative to the suffered low frequency noise, hearing tests should at least include the noise that is measured at the location of the complaint, before conclusions can be made about the audibility. This important condition doesn't discourage conducting hearing tests. It will help in strengthening the correlation in the results. It will lead to a better relation between the researcher and the complainant and should conclusively state whether 'external' or 'self-generated' noise is the cause of the complaints [4].
The test equipment Modorunai is available for research. When new models are made the design can be changed in order to reduce the size.

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