# Why is sharp-limited low-frequency noise extremely annoying?

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Sharp-limited low-frequency noise having only weak components of higher frequencies, such as noise of an air condition or traffic noise attenuated by a thick window, has a very annoying effect on persons also at low levels. The strong fluctuation, which is specific to this kind of sound, is a frequently used explanation for this effect possibly caused by adaptation in the inner ear. Another or additional explanation could be a strong synchronism in the activities on the nerve fibers. Computer models of the auditory system show this synchronism. If some components at higher frequencies are added, the synchronism disappears and the noise is judged less uncomfortable. This raises the question, if noise protection resulting in a sound as described can not be even counterproductive. Differently sharp-limited sounds are investigated by an auditory model and the results are discussed.

# 1 Introduction

Low-frequency noise (LFN) is a sound focused on the frequency range below about 100 Hz. For instance in Germany sound is defined as low-frequency, if the C- and A- weighted sound pressure level (SPL) differs more than 20 dB. For a growing number of people LFN is an urging problem, where a lot of questions are open. A first question could be, why LFN seems to be a greater problem today than in the past. Are the people more sensitive? Or is LFN increasing? Facts for answering the second question can be found.

It can be assumed, that LFN was less common in the past, which doesn't mean, it was quieter. It is difficult to prove but not improbable, that the A-weighting takes the responsibility for the increasing LFN in parts, because A-weighting attenuates LFN strongly. So, in the endeavor to meet the limits in regulations mostly defined in dB(A) it is easier (this means in most cases less expensive) to shift resonances of machines or something like that in the low-frequency range, than to attenuate the vibration or the sound by technical means. More than this effect A-weighting is reproached to lead to an underestimation of the annoyance of LFN.

Another reason for increasing LFN may be found in the growing application of all kinds of noise protection e.g. noise barriers, special windows etc. All these measures have a common property: low-frequency waves can pass through, over or across more unhinderedly than waves in the middle or even in the high frequency range. So, it isn't impossible, that noise protection bears the problem of LFN as it is reported e.g. in [1], where people after measures against noise coming from outside suddenly were hearing LFN, here coming from inside the house, and were so annoyed, that a part of them prefer to sleep with open window in spite of causing a high noise level. [2] deals with a similar problem.

Searching an answer to the question, why some people prefer to endure rather a louder noise with a broader spectrum than LFN with a lower level, only less clues and remarks are to find in the literature. One clue can be found in the detailed LFN-report by Leventhall [3]. According to the reference [4] there, the annoyance of LFN is determined by edge steepness limiting the spectrum of LFN to higher frequencies in the way, that a steeper edge causes an unacceptable annoyance while a moderately steep edge is acceptable. This effect shown in Fig. 1 corresponds to the reaction in [1,2]. So it's the hard-core issue: What can be the basic cause for all these reactions?

In [5] many contributions dealing with the effects of LFN on people come to the assumption, that the special effects of LFN is caused less by the peripheral processing in the outer, middle and inner ear but more by the following processing in the nervous system .

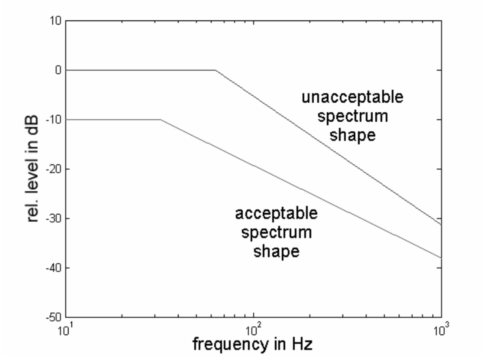



Fig. 1 Acceptable and unacceptable spectrum shapes According to [3,4]

This can explain the direct influence of LFN on the mental health [6], which can be found also in physiological investigations [7].

The spectrum shape seems to be an important characteristic feature and therefore in the following the influence of the spectrum shape should be investigated based on an auditory model including nervous processing. Can reactions be observed different in a typical way, when the model is stimulated by signals with different spectrum shapes?

# 2 Simulation by an auditory model

## 2.1 Used stimuli

There are used two stimuli generated from low-pass-filtered noise, each having an upper frequency limit of 40 Hz, but being different in the steepness of the edge. Fig. 2 shows the time plot of both stimuli lasting 5 seconds.

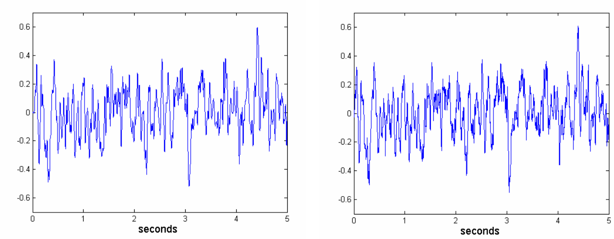



Fig. 2 Time plot of the both stimuli
left: steeply edged ; right: flat edged

In the time plot the difference between both stimuli is nearly invisible. Fig. 3 shows an estimation of the power density spectrum of both stimuli with the clear difference between both.

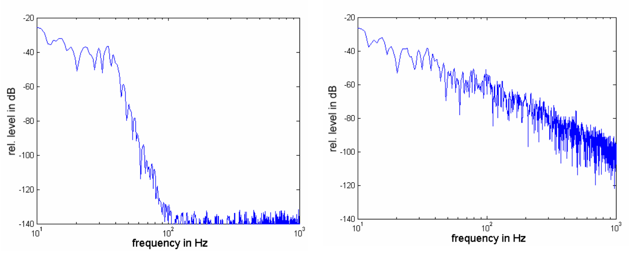



Fig. 3 PD-Spectrum of both stimuli
left: steeply edged ; right: flat edged

Between both stimuli there is also a clear difference by hearing. Certainly both stimuli were perceived as LFN, but the steeply edged noise was obviously more disagreeable for a remarkable part of test persons. It is difficult to describe, what the persons were feeling: most of them were talking about a kind of pressure in the head or about a kind of restlessness. The level of the LFN-signals was here 80 dB(C) in both cases.

The difference between the C- and A-weighted SPL was in the case of the steep edge 38.7 dB, in the other case 26.5 dB. So both stimuli meet the condition of low-frequency mentioned above. It should be seen, that both stimuli have a realistic background, also the steeply edged one. A strong attenuation of middle and higher frequencies can happen for instance during a transmission over a long distance by the air or the soil. It is well known, that far industrial plants can caused LFN in this way [8,9].

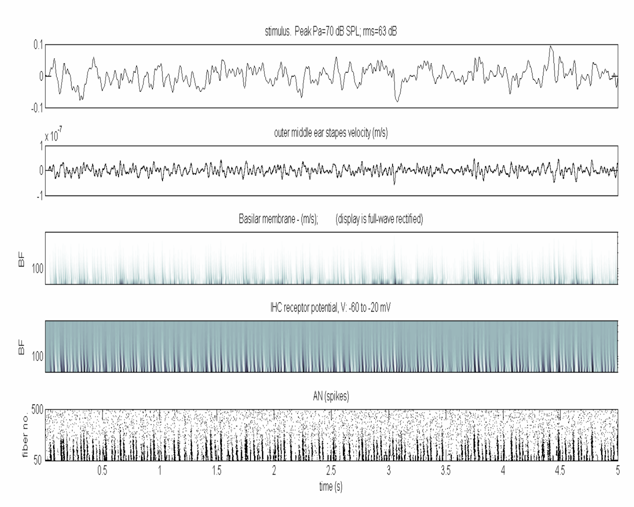
## 2.2 Processing by auditory models

The introduced stimuli were processed by an auditory model to get a look inside, how the acoustical stimulus may be transformed in a nervous stimulus and to get so a better understanding in the process of hearing. While older auditory models are more a collection of algorithms derived from psychoacoustic phenomena, today auditory models try more and more to copy in parts the functions of the auditory system.

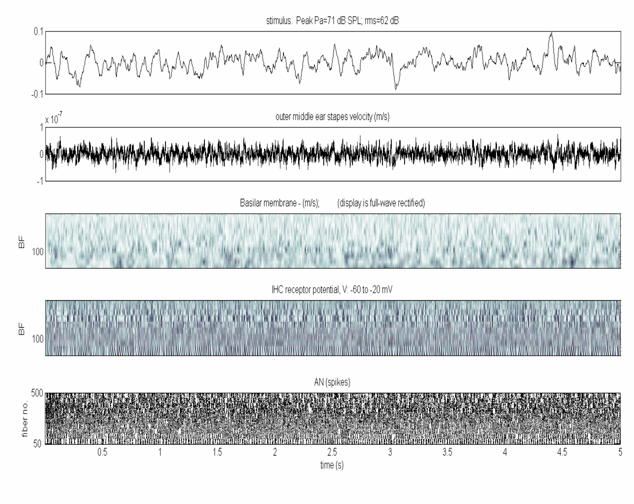
With interest in the reactions on the interface between inner ear and nervous system, that means the reactions of the inner hair cells (IHC), the author searched for models including a hair cell model. There are several proposals regarding such models e.g. [10,11,12,13] and a lot of detailed information about such models can be found in [14]. But it is not easy to write a well working simulation program based only on a theoretical description. In this situation it was very helpful to have some ready-to-used simulation programs to one's proposal by downloading via internet [12,13]. In addition it was a lucky coincidence that since few months the program "MATLAB® Auditory Periphery" (MAP) of Ray Meddis [13] is available, which is be intended for such an application and can simply run in a MATLAB® environment. Beside the program a correct parameter set for the model is very important. Also such ready parameter sets can be downloaded, additionally a plenty of explanations, instructions and demo programs so also users being not specialized in auditory models but interested in related problems can use MAP in an effective way.

## 2.3 Results of the simulations

The following investigations were made using MAP and the plots in Fig. 3 are showing the reaction of the model stimulated by the signals in Fig.2 and Fig. 3




a) Stimulus: steeply edged




b) Stimulus: flat edged

Fig. 4 Plots of the auditory model MAP [13]
from above: stimulus (time plot), tapes velocity, basilar membrane velocity at best frequency (BF) in range from 50 Hz to 500 Hz, IHC receptor potential at BF, spike activity in the range from 50 to 500 Hz

Here most interesting are the plots at the bottom respectively. The spike activities are quite different. While in the case of the flat edged stimulus the spike activities are unstructured over the time, the steeply edged stimulus causes a clearly structured reaction in the spike activities over the time. This means that the activities in the frequency range from 50 Hz to about 500 Hz are synchronized.

It could be assumed, that the synchronism is caused by a fluctuation, which is typical for small band signals.

However a fluctuation of a broad band signal, which can be generated by an amplitude modulation leads to another result, how Fig. 5 shows.

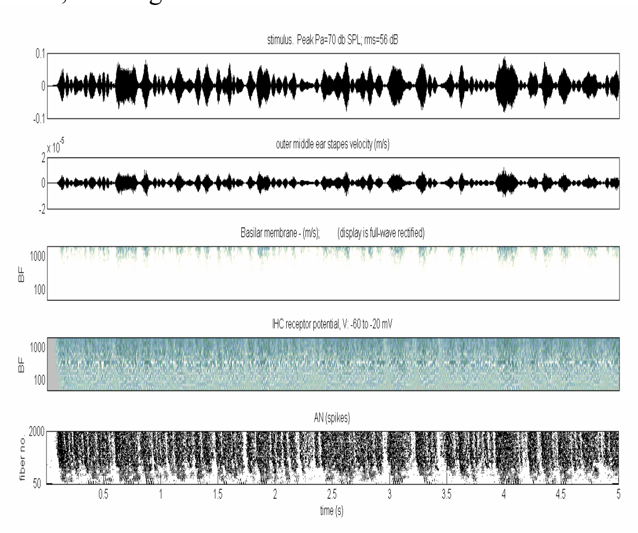



Fig. 5 Plot as in Fig. 4
stimulus: modulated noise

## 2.4 How can synchronism arise?

An explanation of the mechanism leading to the synchronism may be made by the tuning curves, where some are showing in Fig. 6.

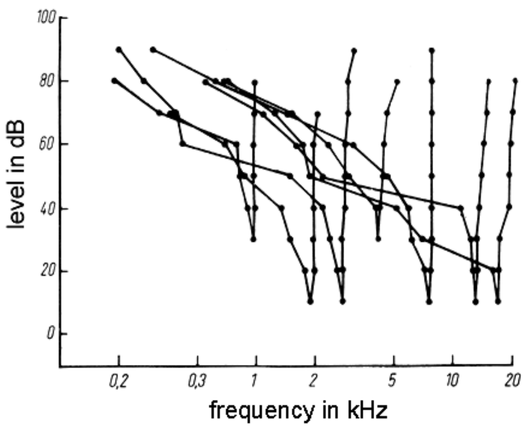



Fig. 6 Tuning curves, from [15]

Tuning curves are developed by choosing a nerve fibre outgoing from an IHC and corresponding with a defined frequency, the so-called best frequency (BF) and then measuring the level of the stimulus at a given frequency, which causes just a reaction on the nerve fibre. The level is the lowest one at BF.

It can be seen in Fig. 5., that the sensitivity is decreasing more rapidly from BF to higher frequencies than from BF to lower frequencies. This results in the case of the steeply edged stimulus in a synchronous stimulation of the nerve fibres above about 100 Hz by the signal components below about 100 Hz. In the case of the flat edged each nerve fibre is exited by the components of the corresponding BF, which are not correlated.

The same condition is fulfilled in the case of the modulated noise. The fibres activities may be more synchronous in the adaptation on the fluctuating stimulus, but less synchronous in the spike activities.

# 3 Discussion

If synchrony is one cause for the special annoyance of low frequency noise, this should not be alerted without further investigations. The search in this direction in publications hardly leads to sufficient results. At least some newer papers point out, that synchronism can shift the threshold of perception down [16,17]. Another aspect, which is worth to think about, is the relatively strong coupling of the auditive with the visual sense [18,19]. So it can be assumed, that processing in both senses are similar. From the visual sense it is well known, that e.g. flickering can cause a synchronisation in the nervous processing, which can bring on an epileptic attack. As reported in [20] also LFN should be able to cause an epileptic attack, but surely this is an extreme situation with a pathological background.

On the other side the part of people, which is very sensitive to LFN, is not to ignore and is estimated to 2.5% in [21]. Beyond it the part of people annoyed especially by LFN may be considerably larger.

As said at the begin of the paper, LFN has a direct effect on the on the mental health [22,23,24] and this is a further indication of a specific reaction in the brain. The phenomenon of the synchronism in the brain activities is a subject of a lot of contributions. Regarding the questions here [25] is interesting, were a connection between synchronous activities in the nervous system and a tinnitus is described. Also the effects of synchronism on the sensory perception, reported in [26], promise a deeper insight into the nervous processing. Many kinds of synchronism are observable in our body, also a relation between a tactile and an auditive stimulation [27]. At high levels such a synchronous multi-sensory stimulation may cause, what is called vibro-acoustic disease (VAD) [28,29].

# 4 Conclusion

Synchronism may be the cause of the specific effects when perceiving LFN. This should be an encouragement to make more investigation in this direction including hearing test, which are - no doubt – necessary. But it is worth to know more details, because the part of people annoyed by LFN is increasing and – this would be alarming – some noise protection application can be conterproductive, if they generate noise with a LFN characteristic.

Investigations based on an auditory model should also be extended to a binaural processing, because the ear signals are nearly identical at low frequencies and that is quite different at middle and higher frequencies. Perhaps here is an additional source for synchronism.

At last the old problem of the A-weighting is waiting on a solution, the underestimation of the LFN annoyance in many situations. May new insights help to solve this problem.

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