Modulation perception and threshold fine structure: Simulations with a nonlinear cochlea model

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Introduction

Many natural sounds show temporal level fluctuations, i.e. amplitude modulations. Thus, a detailed knowledge about mechanisms underlying modulation perception is essential for the understanding of auditory signal processing. Most psychoacoustical studies investigated amplitude modulation processing for carrier levels well above threshold in quiet. The quasi-periodic fine structure in the threshold in quiet commonly observed in normal-hearing listeners affects modulation detection of sinusoidally modulated tones with low carrier levels [2].
The influence of threshold fine structure on modulation detection thresholds is not predicted by current models of modulation perception. This is essentially due to the simplification of the peripheral stages in these models. In order to investigate the potenial role of fine structure in the peripheral preprocessing, the present study uses a one-dimensional active and nonlinear model of the cochlea which simulates a fine structure in the threshold in quiet.
It was shown that in this type of models, the fine structure in various kinds of otoacoustic emissions (OAEs) is connected to the fine structure of the threshold in quiet (e.g. [1]). It was further shown by Zwicker and Schloth [5] that the frequencies of spontaneous otoacoustic emissions (SOAE) often coincide with frequencies where the threshold in quiet shows a minimum. The mechanism underlying fine structure in OAEs and also in the threshold in quiet is thought to be irregularities in the mechanical properties of the basilar membrane and the organ of corti. These irregularities in the mechnical properties and thus in the place-frequency map might give rise to coherent reflections in the area where the excitation pattern is "tall and broad". This "tall and broad" excitation pattern which is found in healthy cochleae needs an active element providing energy to the travelling wave.
The current paper investigated if the difference in performance of modulation detection near threshold can be explained by a reduced modulation depth on the level of the mechanical preprocessing on the level of the basilar membrane. The excitation patterns are modelled with an active and nonlinear 1-dimensional transmission line model of the cochlea. This model was already applied to investigate fine structure in DPOAE [3]. In a first step, a threshold in quiet is simulated with the model including random fluctuations of mechanical parameters along the length of the cochlea. The resulting threshold in quiet is used to apply the experimental paradigm of Heise et al. [2]. In a second step, the representation of amplitude modulation in regions of fine structure at the level of the basilar membrane is analyzed and compared to the performance of subjects in the modulation detection task. The simulations can further enhance our understanding of the relative contribution of temporal and spectral mechanisms underlying modulation perception.

Model description

A 1-dimensional transmission line model which operates in the time domain as previously a e.g. described by [6] was used. The equation of motion for a cochlea partition at position x from the base can be expressed as a second order differential equation:

$$m\ddot{y}(x) + d(x,v)\cdot\dot{y} + s(x)[y(x) + c(v)\cdot y(x)|_\tau] = p(x) \quad (1)$$

with mass per unit area $m = 0.375\text{kg/m}^2$, damping $d(x,v)$ and stiffness $s(x)$ which is driven by a pressure $p(x)$. The displacement is given by y, and the partition velocity by $v = \dot{y}$. The additional delayed feedback stiffness term $c(v)\cdot y(x)|_\tau$ serves to stabilize a negative damping $d(x,v)$. This negative damping in connection with the delayed feedback stiffness term was derived by Zweig [4] from fits to experimental data on BM motion. The time delay τ depends on the resonance frequency of the particular cochlea partition with $\tau = 1.742\cdot 2\pi\cdot\sqrt{\frac{m}{s(x)}}$. The negative damping term and the coefficient of the delayed feedback stiffness are given by $-0.1217\sqrt{ms(x)}$ and 0.1416, respectively. In order to stabilize the model, the negative damping and the delayed feedback stiffness term are adjusted at base and helicotrema. The damping function is given by:

$$d(x,v) = \left[d_l + \frac{\beta(d_h - d_l)|v|}{1+\beta|v|}\right]\sqrt{m\cdot s(x)} \quad (2)$$

and the delayed feedback stiffness term by:

$$c(v) = c_l + \frac{-\beta c_l|v|}{1+\beta|v|} \quad (3)$$

with d_l=-0.12, d_h=0.5 and c_l=0.1416 and $\beta = 0.01$ms/nm. The stiffness is varied to match an exponential place-frequency map as given by:

$$f(x) = A\cdot e^{-a\cdot x} \quad A = 220508,\ a = 150m^{-1} \quad (4)$$

In order to include fine structure, random fluctuations were introduced in the stiffness term:

$$s(x) = s(x) \cdot [1 + 0.01 \cdot N(0, 1)] \qquad (5)$$

where $N(0, 1)$ denotes a normal distribution with zero mean and a variance of 1. All numerical model parameters are chosen according to Mauermann et al. (1999).

Experimental paradigm

The experimental paradigm of Heise et al (2008) was adapted to the finestructure of the model. In the first condition, the carrier was placed at a frequency of 1400 Hz with a level of 15 dB SL and the sidebands at the adjacent minima at 1300 and 1500 Hz (Max condition). In the second condition, the carrier was shifted to the threshold minimum at 1300 Hz with the same SPL as in the first condition (MinSPL condition). The sidebands were shifted to frequencies of 1200 and 1400 Hz. In the third condition (MinSL), the carrier had the same frequency as in the second condition, but had the same SL as in the first condition. The level of the sidebands were -6 dB(m=0 dB) relative to the level of the carrier frequency.

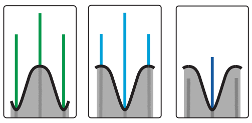

Figure 1: Pictograms of the spectral conditions used in the experimental paradigm by Heise et al. [2]. From left to right: Max condition: the carrier frequency is at a maximum of the hearing threshold while the sidebands are placed in adjacent minima. MinSPL condition: the carrier frequency is placed into a minimum of the threshold with the same level in SPL as in the Max condition. The sidebands are placed into adjacent maxima. MinSL condition: The carrier is presented at the same SL level as in the Max condition.

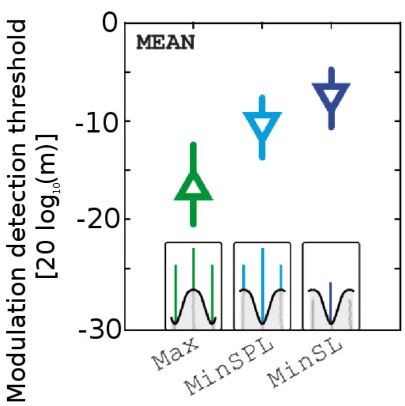

Figure 2: Mean experimental results from Heise et al. (1998). Thresholds are lowest

Results & Discussion

Threshold in quiet

In order to simulate a threshold in quiet, it is assumed that the mechano-electrical transduction at the hair cells is triggered by a certain critical velocity level of the basilar membrane. For sake of simplicity, this level is assumed to be constant in the region of interest. Thresholds are estimated in the frequency region of interest with a frequency resolution of 1 Hz.To estimate the threshold the model is stimulated with a tone with the desired frequency and the level is adaptively varied until the basilar membrane velocity is within a range of 1 dB of the critcial value. The stimulation level

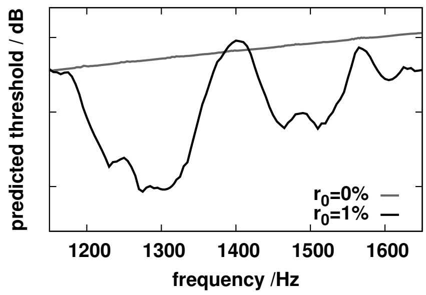

Figure 3: Predicted threshold of the model without (grey line) and with (black line) introduced irregularities in the place-frequency map.

necessary for reaching the critical BM velocity with (black line) and without (grey line) random fluctuations in the place-frequency map (i.e. $r_0 = 1\%$, $r_0 = 0\%$ in eq.5, respectively) is shown in Figure 3. The threshold is a rather smooth function of the velocity with no random fluctuations and shows a fine structure in the simulations with random fluctuations. The simulations show a maximum in threshold at frequencies of about 1180 and 1400 Hz. Minima are at frequencies of about 1300 and 1500 Hz. It is also interesting to note, that the introduction of fine structure increased the sensitivity of the cochlea at most regions compared to the smooth place-frequency map with no random fluctuations.

Ampltitude modulated tones

In order to investigate the representation of modulation on the level of the basilar membrane, the time course of the segment which responded best to the carrier alone (carrier segment) was analyzed. The results of the Max condition are shown in Figure 4. The temporal pattern of the cochleogram shows a modulation with a frequency of 100 Hz, corresponding to the modulation frequency of the stimulus. The modulation is also clearly visible in the time course of the carrier segment (lower panel of Figure 4). This indicates that the modulation of the time-pressure signal is present on the basilar membrane. The simulation results of the MinSPL condition are shown in Figure 5. Similar to the Max condition, the temporal pattern of the cochelogram shows a modulation pattern with a modulation frequency of 100 Hz. Compared to the Max condition, the modulation depth of the carrier segment (lower panel of Figure 5) is reduced.

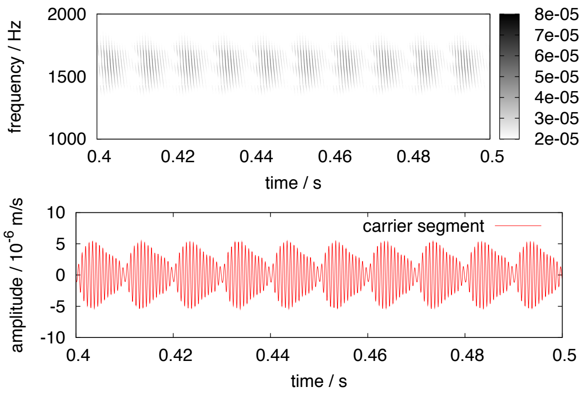

Figure 4: Spectral configuration of condition 1 with a modulation depth of 0 dB. The upper panel shows part of the cochleogram, i.e. the velocity of the single segments (coded in colour) as a function of time. The lower panels shows the time course of the velocity of the carrier segment.

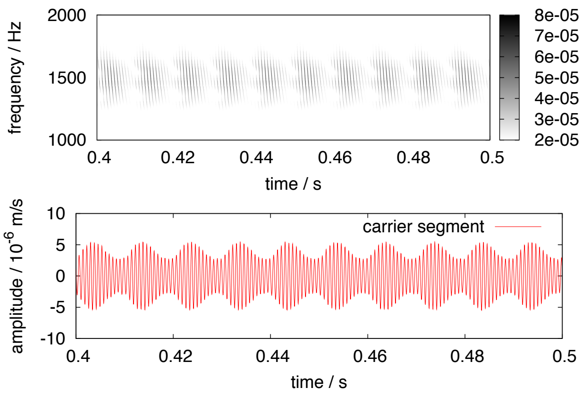

Figure 5: As Fig.4 but for the spectral configutration of condition 2.

The results of the simulations of the MinSL condition are shown in Figure 6. The amplitude of the excitation is reduced compared to the Max and MinSPL conditions. Even at a modulation depth of 0 dB, the amplitude of the carrier frequency is only slightly modulated. This indicates that excitation by the sidebands in regions with reduced sensitivity, i.e. maxima in the threshold, hardly interact with the stimulation at the carrier frequency.
The mean data of the corresponding psychoacoustic experiment (see Figure 2) show, that the modulation detection threshold (MDT) is lowest for condition Max and highest for the condition MinSPL. This is in line with the simulation results. The modulation pattern is most prominent for the Max condition and least pronounced fot the MinSL condition. This indicates, that the finestructure in the sensitivity at different regions of the basilar membrane might be an important factor influencing the modulation depth which is present at the basilar membrane. While side bands well above threshold are interacting with the carrier, the interaction is highly reduced when the side bands are moved into spectral regions with reduced sensitivity. Hence, the reduced performance in MDT in conditions where the sidebands are in regions of a threshold maximum might be due to a reduced modulation depth of the time course of the basilar membrane.

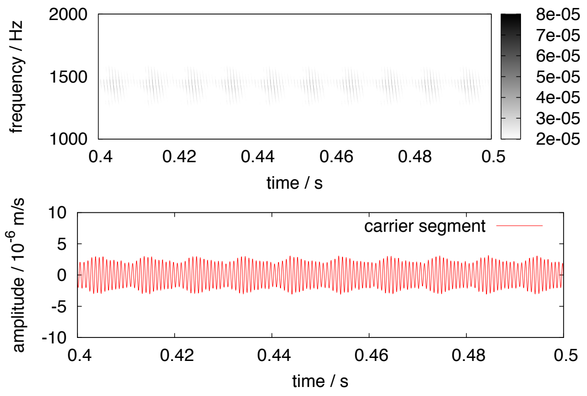

Figure 6: As Fig.4 but for the spectral configuration of condition 3.

Summary

Fine structure in threshold in quiet was simulated with a 1-dimensional non-linear and active model of the cochlea. The model was stimulated with amplitude modulated tones using the same conditions as used in an experimental paradigm by Heise et al. [2]. The simualted results show a difference in the temporal fluctutation of the cochlea partition tuned to he carrier frequency. The results indicate that the difference in performance within the investigated spectral configurations might be the result of a decreased modulation depth on the level of the mechanical preprocessing of the auditory system.

References

[1] Talmadge, C. L., Tubis, A., Long, G. R., Piskorski, P. “Modeling otoacoustic emission and hearing threshold fine structures”. **(1999)**. *J. Acoust. Soc. Am. 104(3), 1517-1543.*

[2] Heise, S. J., Mauermann, M., Verhey, J. L. “Threshold fine structure affects amplitude modulation perception.” **(2009)**. *J. Acoust. Soc. Am. 125(1), EL33-EL38.*

[3] Mauermann, M. and Uppenkamp, S., van Hengel, P., Kollmeier, B. “Evidence for the distortion product frequency place as a source of distortion product otoacoustic emission (DPOAE) fine structure in humans. I. Fine structure and high-order DPOAE as a function of the frequency ratio f2/f1.” **(1999)**. *J. Acoust. Soc. Am. 106(6), 3473-3483.*

[4] Zweig, G. “Finding the impedance of the organ of corti.” **(1991)**. *J. Acoust. Soc. Am. 89(3), 1229-1254.*

[5] Zwicker, E., Schloth, E. ”Interrelation of different otoacoustic emissions“. **(1994)**. *J. Acoust. Soc. Am. 75(4), 1148-1154.*

[6] van Hengel, P. W. J., Duifhuis, H., and van den Raadt, M. P. M. G. ”Spatial periodicity in the cochlea: the result of interaction of spontaneous emissions¿‘ **1996**.*J. Acoust. Soc. Am. 99, 3556-3571.*