Ein Mittelohrmodell basierend auf der Aussenohr-Transferimpedanz

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A middle ear model based on the outer ear transfer impedance

Introduction

In many new research projects, implantable devices are regarded, from simple microphones to complicated actuators with included signal processing units. In this context one has to know the different mechanical loads and impedances which represent the loads of the actuators on the one hand and on the other hand the resulting transfer functions from the excitation to the desired quantities in the middle ear or in the cochlea are of interest. In the literature, many models can be found, ranging from lumped parameter network models to finite element models with several thousand elements. Normally only partial models are identified with measurements, the entire models are too complex for an overall identification and verification by experimental data. On the other hand, the experimental determination of material properties or mass densities e.g. of middle ear ossicles is not feasible without clinical preparation of temporal bone models with the corresponding changes in the material properties during the conservation process.

Network model fitted to the IEC711 data

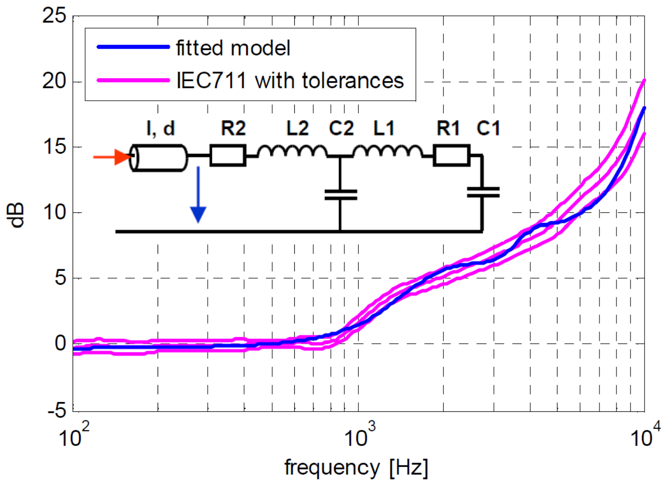

Fig. 1: Outer ear transfer impedance from IEC711 with fitted network model.

The parameters of the ME-model in Fig.1 are determined by a nonlinear model fit to the given transfer impedance as defined in the standard IEC711 [1]. The outer ear canal parameters have not to be fitted because they are given by the standard. For a λ/2-resonance at 14kHz, the corresponding λ/4-resonance lies at 7kHz with a canal length l=14mm. The diameter has to be 7.5mm. Thus, we have the remaining 6 parameters to be determined by the fitting: L2, R2, C2, L1, R1 and C1.

The deviations of the ME-model to the normalized impedance curve from the standard are also plotted in Fig.1 and compared to the corresponding tolerances. It can be observed that the fitted model fulfils the tolerances of the standard. The resulting model values are listed in the following Table 1.

Table 1: Model elements in SI units

C1	2.669e-12	R1	3.967e7	L1	2.970e3
C2	2.040e-12	R2	1.582e7	L2	1.508e3
l	14e-3	d	7.5e-3		

Anatomical interpretation of the model

So far, the model was regarded as a pure acoustical network. For the calculation of the different middle ear transfer functions, it is necessary to split the model in acoustical and mechanical parts. There are some few assumptions to be considered. First, the areas of the ear drum and the stapes footplate have to be determined. In the following, the mean values from Puria [3] are used.

Fig.2 shows the model with the transformations between the different domains. It starts in the acoustical domain in the ear canal, continues over the ear drum transformation into the middle ear mechanics and transforms again to the acoustics in the cochlea. For the ear drum transformation the area Sdr= 66.3 mm^2 is used, and for the stapes footplate area Sst= 3.15 mm^2 is used.

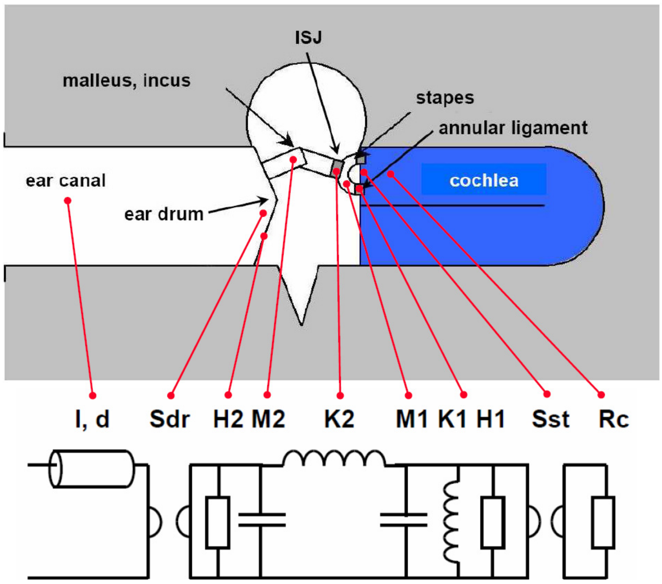

Fig. 2: Relations between middle ear anatomy and model elements. Pressure to velocity transformation at the ear drum with area Sdr and reverse at the round window with area Sst.

One further assumption has to be made: The acoustic damping element R1 has to be divided into a middle ear component (damping of the annular ligament) and a pure cochlea component. This ratio was chosen 20% to 80%.

Comparison with measurements on temporal bones

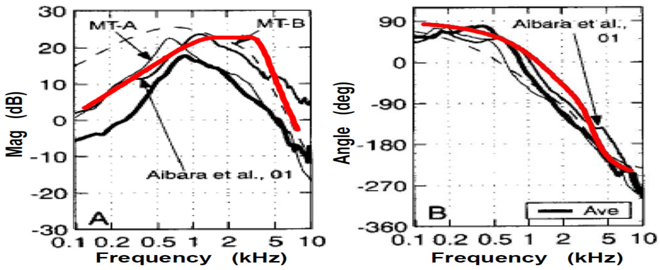

Fig. 3: Pressure transformation outer ear to cochlea. **ME-model**

The pressure transformation from the ear drum to the cochlea was calculated with the ME-model according to Fig.2. In Fig.3 it is compared to a publication from Puria 2003 [3]. For frequencies below 1 kHz the model curve matches well with a typical linear increase from 0 dB to approximately 20 dB at 1 kHz. From 1 to 3 kHz the transformation is more or less constant, at higher frequencies there are bigger differences between different experiments as well as between experiments and model. The relative high values of the model at 3 kHz may be an indicator for a too weakly damped second resonance of the model (value of R2). On the other hand, we do not know how the damping changes in the temporal bones over time.

The phase characteristics in Fig.3 shows an excellent matching between measurements and model up to 10 kHz. The phase change from 90 deg to -270 deg shows clearly that the middle ear transfer function has a characteristics of a low pass filter of 4th order.

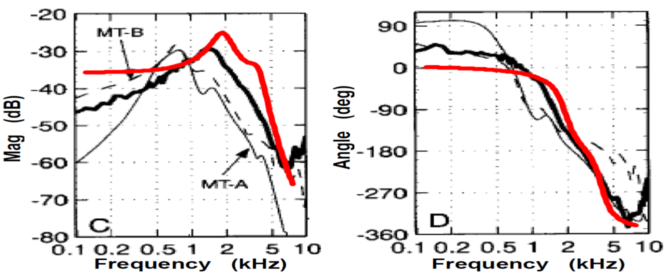

Fig. 4: Pressure transformation cochlea to outer ear. **ME-model**

The reverse pressure transformation from the cochlea to the ear drum is calculated in the reverse direction using the same model. The termination on the ear canal side is given by a closed piece of ear canal tubing, a length of l=10mm was chosen. At higher frequencies, model and experiments lie within of approx. 5 dB. At low frequencies, the model curve is flat as expected for a closed volume. It seems that the measurements on the temporal bones were not free of leakage. For such small volumes even small slits lead to a pressure decrease as observed in Fig.4. Of course, the difference in the amplitude slopes is visible in the corresponding phase shapes too. For high frequencies, the matching of the phases is excellent.

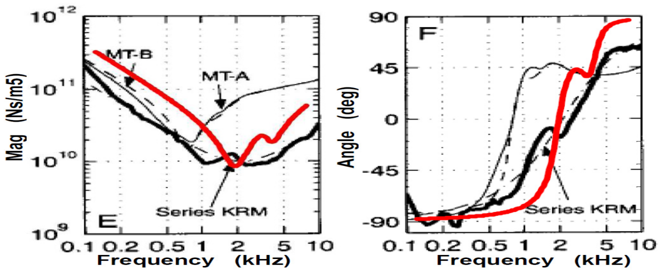

Fig. 5: Reverse middle ear impedance. **ME-model**

The middle ear reverse impedance is of importance in the context of cochlea actuators. This mechanical load can be regarded with or without the cochlea impedance in parallel. For the comparison with the Puria data [3] the reverse impedance without Rc is plotted in Fig.5. The total compliance of the ME-model at low frequencies tends to be somewhat too high, while it depends on the residual ear canal volume. In this configuration where is no cochlea damping acting, two pronounced middle ear resonances are visible in the measurements as well as in the model.

Conclusions

The middle ear model presented in this paper is most probably the simplest possible one. It is based on pure acoustical data from the outer ear and uses the knowledge about middle ear anatomy. The main characteristics of this lumped parameter ME-model are:

- Chain structure of compliance and mass elements
- General low pass characteristics 4th order
- Real cochlea input impedance
- Acoustical-mechanical coupling by gyrators with defined areas, also applicable to pistons
- Can be used for coupling of middle ear or cochlea actuators
- Provides adequate mechanical loads for sensors and actuators
- Allows modifications for simulation of middle ear diseases
- Signal flow in forward and reverse direction possible (otoacoustic emission applications)
- Simple enough for complete numerical parameter fit to measured ear canal impedances
- Matches IEC711 ear simulator impedance

Literature

[1] IEC 60711, Edition: 1.0, Chg: Date: 01/00/81, “OCCLUDED-EAR SIMULATOR FOR THE MEASUREMENT OF EARPHONES COUPLED TO THE EAR BY EAR INSERTS”.

[2] Stirnemann, Alfred. “Impedanzmessungen und Netzwerkmodell zur Ermittlung der Uebertragungseigenschaften des Mittelohres“ (1980). doi:10.3929/ethz-a-000215254.

[3] Sunil Puria. “Measurements of human middle ear forward and reverse acoustics: Implications for otoacoustic emissions”. J. Acoust. Soc. Am. 113(5) 2773 (2003).