Estimation of the Sound Pressure at the Ear Drum for Hearing Aid Applications

Tobias Sankowsky[1], Matthias Blau[1], Philipp Roeske[1], Hamidreza Mojallal[2], Jens Schroeder[2], Magnus Teschner[2], Martin Bokemeyer[2]

[1] *Institut für Hörtechnik und Audiologie, FH Oldenburg/Ostfriesland/Wilhelmshaven*

[2] *Medizinische Hochschule Hannover*

Introduction

The sound pressure at the ear drum is a reference quantity in hearing aid fitting. The direct measurement can be difficult and unpleasant for the patient, so that a suitable method for predicting the sound pressure at the ear drum would be beneficial. There are several models for transfer functions of mean ear canals, however assuming an inappropriate transfer function of a mean ear canal may lead to errors up to 20 dB at 4 kHz [1]. The availability of wideband receivers enables hearing aid fitting for an extended frequency range up to 10 kHz where individual ear canal transfer functions differ up to 20 dB [2].

One approach for the estimation of the sound pressure at the ear drum is to establish a 1D model of the residual ear canal, based on the measured acoustic impedance at the interface between the ear shell and the residual ear canal. In a study on 10 human temporal bones (TB) with closed ear shells, 1D models established this way were used to predict the drum pressure in the 100Hz..10kHz frequency range.

The models were all based on the same measured impedances, but several variants of algorithms to derive the ear canal models were employed. Impedance measurements were done with a calibrated source with 3 parameters according to [3]. For calibration 3 cavities and 3 tubes were used.

Modeling the ear canal

The basic approach for the prediction of a transfer function of the individual ear canal is published in [4]. Wherein it's exposed that the reflectance above 3 kHz substantially depends on the cross section function of the ear canal. The reflectance is given by

$$R(f) = \frac{Z(f) - Z_{\mathrm{w}}}{Z(f) + Z_{\mathrm{w}}}\ , \text{ with } Z_{\mathrm{w}} = \frac{\rho c}{3.5^2 \mathrm{mm}^2 \cdot \pi}, \qquad (1)$$

where $Z(f)$ denotes the acoustic impedance and Z_{w} is the wave impedance. Therefore a parametric cross section function is searched with a transfer matrix which leads to the same reflectance. The required termination of the ear canal is modeled according to [5]. A representation of the ear canal model is given in figure 1 where ear canal model denotes the estimated transfer matrix determinated by the cross section function from the entrance at the ear shell to the defined plane of the ear drum. Z_{D} denotes the impedance of the ear drum and is located 4 mm in front of the inner most end of the ear canal. The impedance Z_{t} accounts for the definition of the plane of the ear drum and is given by a cavity of circular cross section with a linearly decreasing radius from 2.5 mm to 0 mm.

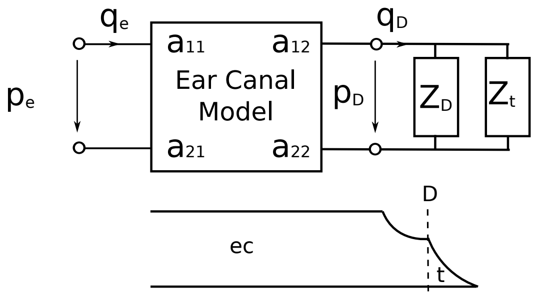

Figure 1: Transfer matrix model of the ear canal with a sketch showing the plane of the ear drum labeled with D.

For parametrization of the cross section function the first parameter is the length l_x of the ear canal. The second till N$^{\mathrm{th}}$ parameters are coefficients a_n of sine terms of a Fourier series. For the ear canal model two different equations were tested. The first one according to [4] is given by

$$r(x) = r_0 + \sum_{n=1}^{N-1} a_n \sin\left(n 2\pi \frac{x}{0.1\mathrm{m}}\right), \qquad (2)$$

$$\text{with } l_0 \le x \le l_{\mathrm{e}}$$

where r_0 is the radius of 2.5 mm at the plane of the ear drum and l_{e} is the length of the ear canal. The second model equation is given by

$$A(x) = A_0 + \frac{A_e - A_0}{l_{\mathrm{e}}} x \sum_{n=1}^{N-1} a_n \sin\left(n\pi \frac{x}{l_{\mathrm{e}}}\right), \qquad (3)$$

$$\text{with } l_0 \le x \le l_{\mathrm{e}}$$

where A_0 denotes the cross section of $(2.5\ \mathrm{mm})^2 \cdot \pi$ at the ear drum and A_e is the cross section of the ear canal at the shell. For determining the reflectance of the estimation R_e a transfer matrix of 32 tube segments is calculated from the cross section function. Than the estimation error is calculated by

$$e = \sum_{f=3000\mathrm{Hz}}^{10000\mathrm{Hz}} \left(\arg\{R_m(f)\} - \arg\{R_e(f)\}\right)^2 |R_m(f)| \quad (4)$$

where R_m is the measured reflectance and $\arg\{\cdot\}$ is the unwrapped phase.

The fitting procedure is as follows: For an initial parameter set the estimation error will be calculated. The first parameter which is the length of the ear canal will be varied about the variation width $\pm\Delta x$. In the case that the new parameter set leads to a smaller estimation error the change in length will be adopted except for a random factor between 0..0.5. The variation width than will be increased by 5% and the fitting starts again at the first parameter. In the case that the new parameter set doesn't lead to a smaller error the old length will be hold and the variation will be tested on the second parameter in the same manner. If the variation of any parameter doesn't lead to a smaller estimation error the variation width Δx will be decreased by 50%. The fitting algorithm stops if a minimum of the variation width is reached.

Four variants of the Algorithms were compared which differ in the used model equation and the number of parameters.

1. Model equation 2, with 10 parameters and an initial Δx of 3 mm for all parameters is used.
2. Model equation 3, with 4 parameters and an initial Δx of 3 mm for the length and a Δx of $(3\text{ mm})^2 \cdot \pi$ for the coefficients a_n is used.
3. Model equation 3, with 2 parameters and an initial Δx of 3 mm for the length and a Δx of $(3\text{ mm})^2 \cdot \pi$ for the coefficients a_n is used.
4. Model equation 2, with 2 parameters and an initial Δx of 3 mm for all parameters is used. If the algorithm stops the number of parameters N is increased by 2, the initial Δx is set to $3\text{ mm}/(N-1)^2$ and the algorithm starts again. This is repeated till 10 parameters are reached.

Even though the differences in the estimated cross section functions between the variants of the algorithms are large the differences in the transfer functions are small. Figure 2 shows the transfer functions of the sound pressure at the drum p_D relative to the sound pressure at the entrance p_e and relative to the volume velocity at the entrance q_e for the TB 1..4 and for the different variants of the algorithm. The deviations between the variants of the algorithm in the case of p_D/p_e in the range of ± 2 dB at 10 kHz except for one estimation of TB 2 where the deviation between variant 2 and 1 reach 6 dB at 10 kHz. The same estimation leads to a deviation in the transfer functions p_D/q_e of variant 2 and 1 where the difference is about 4 dB between 2..10 kHz. The deviations between the algorithm variants of the other estimations of p_D/q_e are smaller than ± 1 dB.

For TBs 5..10 only the variants 1 and 4 could be applied to because the cross section of the entrance of the ear canal is required for the other variants. These cross sections are determined from computer tomography data of the TB with the ear shell which were not available yet. The estimated transfer functions and the deviations between the variants of the algorithms are depicted in figure 3. The deviations between the variants for the

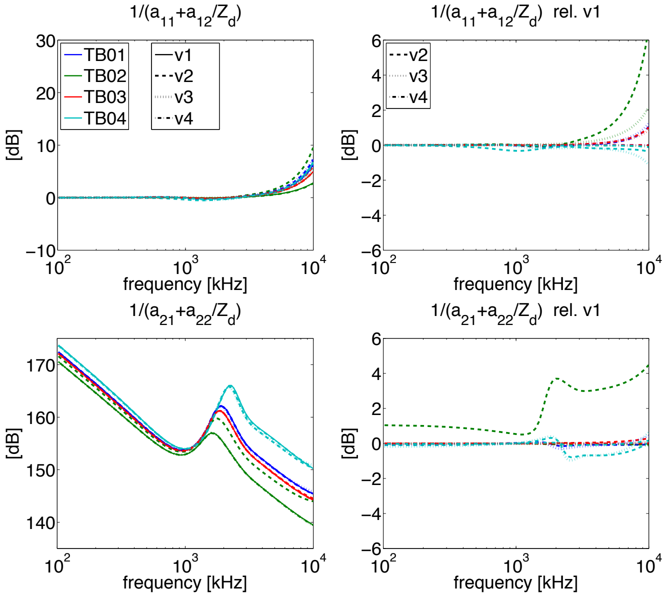

Figure 2: Temporal bones 1-4. Top left: Sound pressure at the drum p_D to sound pressure at the entrance p_e.Top right: Deviation in p_D/p_e to variant 1. Bottom left: Sound pressure at the drum p_D to volume velocity at the entrance q_e. Bottom right: Deviation in p_D/q_e to variant 1.

transfer function p_d/p_e are smaller than 1dB except for TB 9 where they reach slightly more than 5 dB between 9..10 kHz. The deviations in the transfer functions p_D/q_e do not exceed 2 dB.

Sound pressure at the ear drum

For a comparison of measured and estimated sound pressure at the ear drum a model of the source is required whereby the transfer function sound pressure at the drum to receiver voltage p_D/u can be calculated. Such a model has been determined from measurements of the source connected to tubes of known length.

The representation of the benefit caused by the estimated transfer functions of the ear canal is illustrated in figure 4. For all predictions the variant 4 of the algorithm is used. The interindividual variation of the measured transfer functions p_D/u is shown in the upper diagrams and the deviation between measured and estimated p_D/u is shown in the lower diagrams. Results for TBs 1..4 are shown on the left side, results for TBs 5..10 are shown on the right side. One source model has been used for the TBs 1..4 and another source model has been used for TBs 5..10. The large deviations below 800 Hz are due to the fact that the ear shells don't seal the ear canals of the temporal bones properly. The influence of the ear canal geometry on the sound pressure at the drum is seen above 1 kHz. There is a common trend in the deviations between measured and estimated p_D/u which indicates a deficiency in the source models.

For TBs 1..4 the interindividual variations in the measured sound pressure are not very large. The variations are in the range of -9..5 dB. The length of these ear canals was about 6 mm which is relatively short. There is a slight benefit in using the estimated ear canal model,

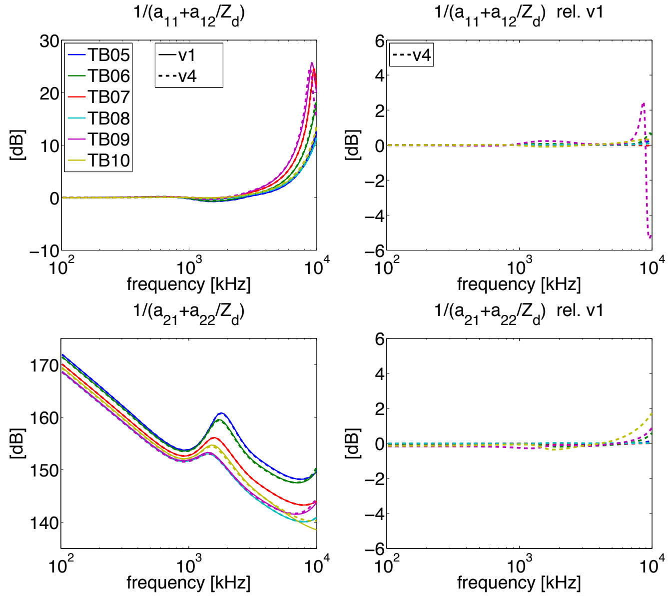

Figure 3: Temporal bones 5-6. Top left: Sound pressure at the drum p_D to sound pressure at the entrance p_e.Top right: Deviation in p_D/p_e to variant 1. Bottom left: Sound pressure at the drum p_D to volume velocity at the entrance q_e. Bottom right: Deviation in p_D/q_e to variant 1.

resulting in variations that are in the range of -6..6 dB.

With the focus on the frequency range above 1 kHz the interindividual variations of measured p_D/u for TB 5..10 takes values from -10..12 dB. The benefit in using the estimated ear canal model is clearly seen. Variations were reduced and take values of -5..6 dB.

Conclusion

The estimation of a a transfer function of an individual ear canal from the measured entrance impedance leads to an appropriate prediction of the sound pressure at the ear drum for a frequency range from 1..10 kHz. The different variants of the fitting algorithm lead to large differences in the cross section function of the ear canal, whereas the differences in the estimated sound pressure at the ear drum are small. Variant 4 of the algorithm leads to the best agreement between measurement and estimation. Furthermore, variant 4 has the most robust performance.

In further work this methodology will be applied to individual patients. Initial tests indicate that the sealing of ear shells in subjects ears is much better than in TB which leads to a good agreement of measured and estimated sound pressure in the frequency range considered.

Acknowledgment

This work was supported by Audiologie Initiative Niedersachsen.

References

[1] D. B. Hawkins and J. A. Cook. Hearing aid software predictive gain values: How accurate are they? *The Hearing Journal*, 56(7):26–34, July 2003.

[2] M. Blau, T. Sankowsky, P. Roeske, and S. Fischer. Predicting the acoustics of individual ears for hearing aid and audio applications - model framework and future work. In *NAG/DAGA*, 2009.

[3] A. Stirnemann, H. Graf, and H. Meier. Akustische Impedanzmessungen in der Hörgerätetechnik. *DAGA*, 2003.

[4] A. Lodwig. *Ein System zur Anpassung von Hörgeräten - Meßtechnik, patientenbezogene Modellierung, Optimierung der Komponenten*. PhD thesis, Ruhr-Universität Bochum, 1998.

[5] H. Hudde and A. Engel. Acoustomechanical human middle ear properties. part iii: Eardrum impedances, transfer functions, and model calculations. *ACUSTICA/acta acustica*, 84:1091–1108, 1998.

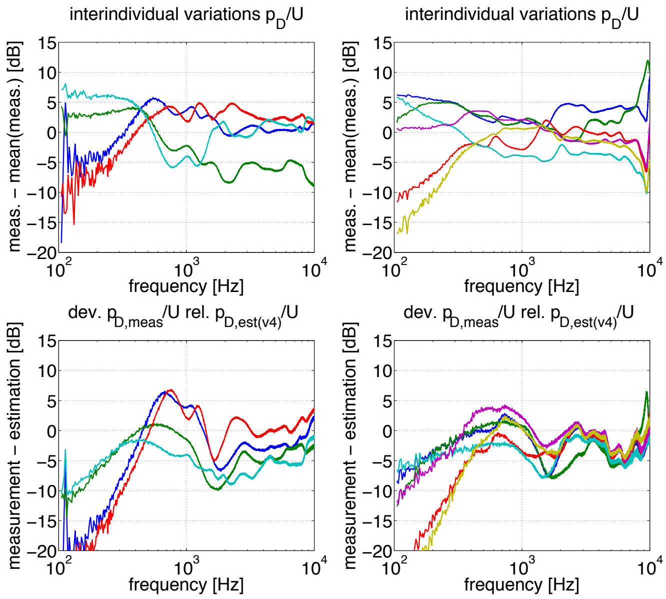

Figure 4: Top: Interindividual variations of measured p_D/u. Bottom: Deviation between measured and estimated p_D/u. Left: TB 1..4. Right: TB 5..10.