Simulation and Measurement of the Pressure at the Eardrum Emitted by Hearing Aids in Auditory Canals Occluded with Custom Ear Molds

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Introduction

Despite other suggestions, the pressure in direct vicinity of the tympanic membrane (TM) is believed to be a reference quantity for the further perception of sound [1]. If the characteristics of the sound source (e.g. a hearing aid receiver) are known, the sound pressure resulting at the TM depends on the acoustical load. This acoustical load when wearing a hearing aid, mainly determined by the geometry of the auditory meatus and the reflection properties of the TM and middle ear, is individual and apriori unknown. Hence, the sound pressure emitted by the hearing aid varies when the same device with the same setting is applied to different subjects. In order of a modern hearing aid fitting, real ear measurements (REM) are a recommended standard to account for the inter-individual acoustic loads. Alternatively, for the case of occluded earcanals by custom molds, previously a simple model of the middle ear was developed, which sufficiently accounts for transfer characteristics from the acoustic wave in the meatus to mechanic movement of the TM and ossicle chain [2]. Within this simplified generic model an acoustic measurement for frequencies up to 7.5 kHz is suited to describe the further transmission. At higher frequencies the measurement becomes sensitive to changes in boundary conditions. Nevertheless, these findings were based on a simplified generic model. In addition to the generic model, results of coupled acoustic-mechanical Finite Element Simulations for realistic geometries of the auditory meatus are investigated in this study. The sound pressure at the umbo of the model is compared to the related reference REM. Moreover, a two-port network model considering data from literature and measurements on plastic casts of the earcanals are also included in the comparison. Two questions should be answered. On the one hand, it is investigated, whether the model using the Finite Element Method (FEM) can sufficiently predict the sound pressure in front of the tympanic membrane p_{TM} (assuming REM as a reference). And on the other hand it should be answered, if there are advantages of the FEM model compared to the models in literature and the measurement in the model cast. To this end, an individual FEM model for three adult subjects was constructed, a custom ear mold was manufactured and a REM was taken as the reference.

Finite Element Model

The geometry for the Finite Element Simulation were derived from casts of earcanals of three subjects. The imprints were made of silicone-like material usually used in the procedure to manufacture custom ear molds. For the special purpose, the imprints reached up to the TM. Hence, extraordinary care had to be taken, in order to not harm subjects. A three-dimensional optic scanner was used to digitize the imprints to a triangulated surface mesh, which is depicted in Figure 1. Further, geometric parameters such as the centerline are extracted. As pointed out before, the meatus is occluded by a standard custom ear mold (designed and manufactured as it is done in practice) on the lateral end, which leads to a shorter model compared to the length in Figure 1. Due to flexibility in defining boundary conditions and incorporate the eardrum and middle ear, sections cross-sectional to the centerline (found by an algorithm close to the procedure of [3]) are used to generate a simplified mesh. Figure 2 shows an exemplary result of the procedure for subject 1. As a measure for the difference between the original and simplified geometry, the Hausdorff distance for every case was computed. In average the Hausdorff distance was smaller than 0.3 mm with a maximal value of 1.2 mm for subject 1 (depicted in Fig-

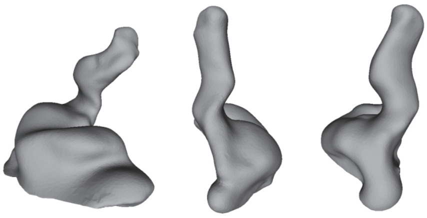

Figure 1: 3D scanned imprints of the auditory meatus of the three subjects (1-3 from left to right)

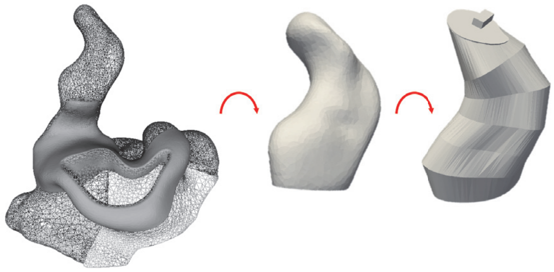

Figure 2: 3D view on the assembled FE-model with its basic properties

ure 2). On the medial end, the model of the tympanic membrane including the middle ear load of [2] is used to account for the reflection properties. This middle ear model is connected to a cross-sectional slice by adjusting the volume in such a way, that it meats the volume of the innermost (10 mm on the centerline) part of the original geometry. Additionally, at the interface of the mold and the connected earcanal, on a circular plane of 1 mm in diameter, the system is excited by a normal velocity (compare to [2]). The resulting model can be seen in the right part of Figure 2. Mesh generation was done in Gmsh [4]. Only harmonic excitation was considered. Equation (1) shows the acoustic-mechanical coupling condition, which is set for the connecting interface of the modelled eardrum. The acoustic particle velocity $\boldsymbol{v}_\mathrm{a}$ normal to this interface equals the mechanical velocity $\boldsymbol{v}_\mathrm{m}$ in this direction

$$\boldsymbol{n} \cdot (\boldsymbol{v}_\mathrm{a} - \boldsymbol{v}_\mathrm{m}) = 0\,. \tag{1}$$

The resulting system of partial differential equations was solved by the Finite Element code CFS++ [5].

Measurements setups

In this study, two types of measurement were accomplished. On the one hand, probe tube measurements were done on a cast of earcanal 1, which was 3-D printed and is shown in Figure 3. The material is believed to be sound rigid. On the other hand, for every subject a REM, which serves as the reference was taken. For both purposes the Etymotic ER-7C microphone was used. In every custom mold, one bore to connect the hearing aid receiver and an extra bore for the probe tube was manufactured (3-D printing). The setup at the real ears is the same as shown in Figure 3. A Knowles Balanced Armature Receiver ED21913 was used as sound source. The characteristic of the receiver coupled to the custom mold was determined by measuring the response in an artificial ear Type IEC 60318-5 with a known transfer impedance Z_T. Dividing the pressure measured at the coupler microphone p_C by Z_T gives the sound flux q_S of the excitement for every frequency and a specific driving voltage U_S. Signal presentation (sine-sweep) and recording was done with a Laptop Computer connected to an RME Fireface soundcard. Further processing was done in Matlab. Time signals were windowed by a Hanning-window and transformed to frequency domain via a standard FFT method.

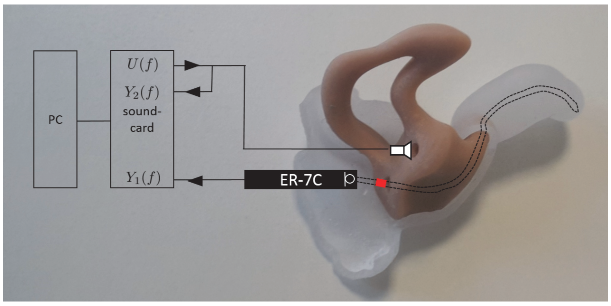

Figure 3: 3-D printed cast of the auditory meatus of subject 1 with the measurement setup

For the REM the probe tube was placed by inserting the tube until the subject felt contact with the eardrum. This position was marked with a small extra ring on the tubing at the outer face of the custom mold. Finally the tube was slightly pulled away from the TM by less than one millimetre.

Network model

In order to compare the results of the FEM model, a network model with data from literature was used. The model framework is close to the one of [7], whereas here leakage was not taken into account. For the "eardrum impedance" Z_D the data of [6] was used. No further individual adjustment to account for the inter-individual differences of the reflection properties at the tympanic membrane was done.

Results

Before comparing the models to the REM it has to be verified, that the reconstruction of the geometry and the coupling of the generic middle ear does not change the acoustic properties when compared to the original geometry. Therefore, three cases were simulated. First, the original geometry at sound hard boundary conditions (ref geo) and second, the modified geometry on the one hand at sound hard boundaries (mod geo A) and on the other hand including the acoustic-mechanical coupling at the tympanic membrane (mod geo A/M) were calculated. The comparison is exemplary shown for subject 1 in Figure 4 The sound hard cases ref geo and mod geo A up to 7.5 kHz are in excellent accordance (< 1.5 dB). The comparison of the sound hard cases to the coupled case also shows good accordance in the high frequency range from 2-7.5 kHz. In the lower frequency range a drop of the sound pressure level due to the coupling can be seen. As shown in Figures 5 - 7 an analogue effect can be ob-

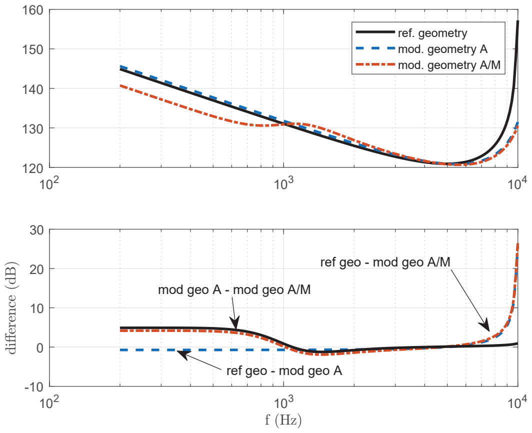

Figure 4: Comparison of Simulations of the original geometry with sound hard boundary conditions and the modified geometry.

served for the REM for each subject. Hence, in quality, the acoustic-mechanical coupling is able to account for the reflection properties at the tympanic membrane. To fit the model prediction to the REM the thickness of the tympanic membrane as well as the Young's modulus of the middle ear model were adjusted. The results in the frequency range up to 6 kHz differ from the measurement by less than 4 dB for every subject. Extending the range up to 9 kHz leads to deviations less than 11 dB. Figure 8 shows the exemplary results of the sound pressure level (SPL) at a remote point in front of the tympanic membrane of subject 1. The reference measurement on the real ear is depicted as the black line. In contrast to Figures 5 - 7 the SPL is depicted as absolute values, which includes the characteristics of the receiver. The curves show two main resonances, one the one hand, the receiver resonance around 2.8 kHz, and on the other hand a Helmholtz resonance due to the sound bore through the mold (receiver is coupled at the outer face of the mold). At frequencies above 7 kHz higher harmonics of these resonances are present.

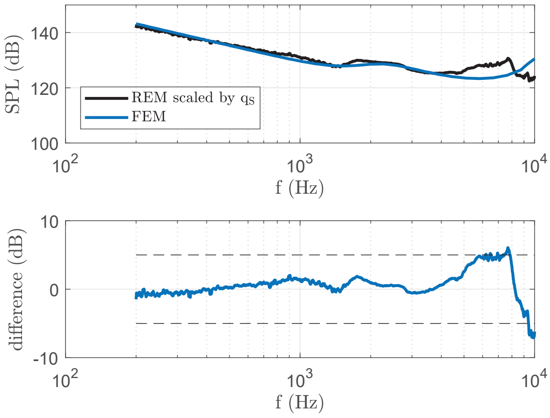

Figure 5: Measured and modelled sound pressure level at a remote point in front of the tympanic membrane for subject 1 normalized to a constant normal source velocity of 1.

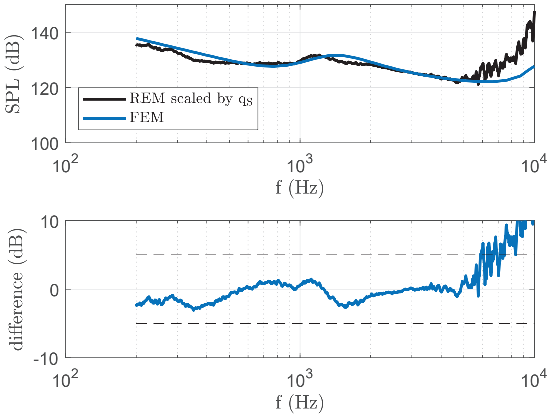

Figure 6: Measured and modelled sound pressure level at a remote point in front of the tympanic membrane for subject 2 normalized to a constant normal source velocity of 1.

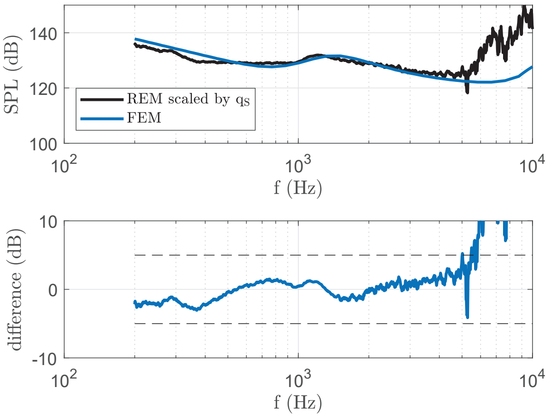

Figure 7: Measured and modelled sound pressure level at a remote point in front of the tympanic membrane for subject 3 normalized to a constant normal source velocity of 1.

Compared to the measurement in the sound rigid cast, mainly in the low frequency range from 200 Hz to 1 kHz deviations around 5 dB occur. In the range of 2 kHz to 6 kHz the difference becomes smaller than 3 dB. Especially the receiver resonance is in good accordance. For the Helmholtz resonance slight shift in frequency can be observed. At frequencies higher than 8 kHz the difference in SPL of the REM to the measurement in the cast become higher than 5 dB and reaches up to 20 dB. Regarding only the range up to 7.5 kHz, the main deviations are in the low frequency range and in average are less than 5 dB.

A similar behaviour can be observed by comparing the network model to the REM. In this model the reflection properties of the TM in form of an average "eardrum impedance" are taken into account [6]. Although, the effect of the eardrum is shifted in frequency and the decrease in SPL compared to the sound hard case is not as distinct as for the finite element model, in quality it gives the same impact on the overall SPL.

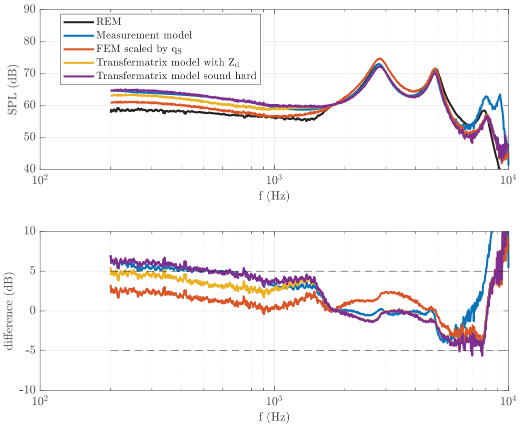

Figure 8: Measured and modelled sound pressure level at a remote point in front of the tympanic membrane.

Discussion

The results show a good accordance of the acousto-mechanical coupled finite element model. One major finding is that the assumption of sound hard boundaries is sufficient for frequencies higher than 1.5 kHz. In the range up to 7 kHz, all models meet the measured SPL in real ears. Still, for lower frequencies the influence of the middle ear on the ear canal acoustics becomes obvious by a drop in SPL. The frequency at which this drop occurs, as well as the difference in SPL compared to the sound hard case, was find to be individual. The difference to the sound hard case in this study was higher than the average "eardrum impedance" of [6] suggested, while in quality the impact is comparable. For the FEM model two parameters could account for this effect. On the one hand this is the thickness of the eardrum, and on the other hand it is the Young's modulus of the middle ear model, which can be adjusted to meat the REM. Clearly, these parameters could only be identified by the multi-physics model, which is a main advantage compared to the other models. Nevertheless, the realistic values where not validated by measurements. Moreover, the study only comprises fully occluded cases. As turned out during the REM, for many cases, some leakage respectivly vents has to be taken into account. If also for these cases the model is able to predict accurate results, needs to be further investigated. Finally, it has to be mentioned, that REM have limitations by means of the frequency range up to which they give a good measure for the further sound perception. As pointed out e.g. in [2] at frequencies higher than 7.5 kHz higher order modes occur. This might also be a reason for the deviations between the models and the REM.

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