A Finite Element Approach to Evaluate the Validity of Real-Ear Measurements as an Auditory Reference in Occluded Human Ears

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Introduction

In many audiological applications the sound pressure in direct vicinity of the tympanic membrane (TM) is used as a reference for the further perception of sound. E.g. for hearing aid fitting, the desired target gain can be adjusted by means of so called in situ or real-ear measurements (REM). The transmission in the middle ear is a mechanical movement of the TM and ossicles, resulting in the stapes footplate acting on the vestibular window. Using the finite element method (FEM), a coupled three-dimensional (3D) model considering both acoustics and mechanics has been generated. The model takes an occluded auditory meatus and an optional venting into account. With this model, two main issues are investigated. On the one hand, the transversal pressure variations in the auditory meatus, especially in front of the TM are examined, when the interaction with the complex movement is taken into account. And on the other hand, the influence of the boundary is investigated. Obviously, the acoustic pressure changes due to variations of the load. For example, the sound pressure in the auditory canal would be completely different, for the case with an otoplastic and without an otoplastic. The same applies to less apparent changes, such as altering the shape or length of the mold. Nevertheless, it is apriori unknown, if the changes in acoustic also change the further transmission, thus the motion of the TM and middle ear in the same manner. Therefore, this transmission behaviour due to changes in the boundary is investigated. This is done by respectively modelling an increasing medial insertion depth of the mold, leading to a shorter remaining length. Finally, a valid range in which a single REM represents the transmission characteristic is rated.

Finite Element Model

Table 1: Material properties

	Parameter				
	K (N/m^2)	E (N/m^2)	ρ (kg/m^3)	ν	$\tan(\delta)$
TM		$35 \cdot 10^6$	1200	0.4	1.2
ME Load		$12 \cdot 10^9$	2700	0.4	1.2
Air	$1.4 \cdot 10^5$		1.14		

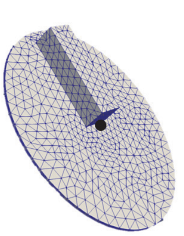

Figure 1: Simplified model of tympanic membrane

The morphology of the TM and the ossicle chain is modelled by a loaded plate, as shown in Fig. 1. In the following, the movement of the umbo (marked with a black dot) is assumed to be the measure of further sound perception. The validation for the umbo displacement is shown in the results and additionally revisited in the discussion. The membrane part has the properties of the pars tensa and the embedded load mass representing the middle ear by its mass and a Young's modulus of bony structures. Further, material properties are given in Table 1, where K is the bulk modulus, E the Young's modulus, ρ the density, ν the Poisson's ratio and $\tan(\delta)$ is the loss factor. The model further considers an optional venting. Therefore, the vent itself is modelled as a rigid tube connected to a free field box, as depicted in Fig. 2. Due to that, effects of the pinna are neglected and sound waves from the vent directly radiate into free field (modelled by a Perfectly Matched Layer technique). The inner face of the otoplastic is modelled as sound rigid, while the excitation is prescribed on a sub-area (circular area of r=0.5 mm) on this inner face. For all simulations the constant normal acoustic particle velocity on this excitation plane was set to a value of $\boldsymbol{v}_{\text{exc}} = 2 \cdot 10^{-3}$ m/s. All other boundary conditions are set as sound hard.

Mesh generation was done in Gmsh [1]. For acoustics, the discretization size was $h_{\text{a}} = 2.6 \cdot 10^{-2}$, while for the middle ear mechanics a coarser mesh with $h_{\text{m}} = 5 \cdot 10^{-3}$ was used. Only harmonic excitation was considered. Equation (1) shows the acousto-mechanical coupling condition, which is set for the connecting interface of the modelled eardrum. The acoustic particle velocity $\boldsymbol{v}_{\text{a}}$ normal to this interface equals the mechanical velocity $\boldsymbol{v}_{\text{m}}$

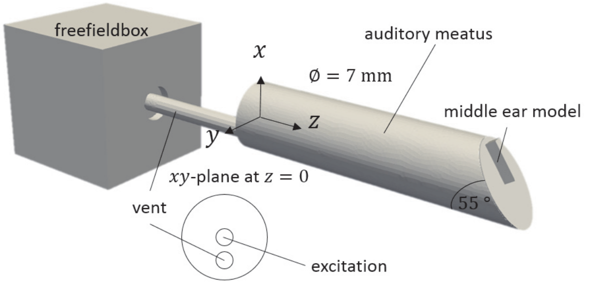

Figure 2: 3D view on the assembled FE-model with its basic properties

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++ [2].
Figure 3 shows the 3D domain on the right and the sectional view on the left. To study the transversal variations, the sound pressure at five monitoring positions over the cross section is chosen, as depicted by the blue lines. For each cross-sectional position, 200 points are distributed over the length of the meatus.
Second, to investigate, if the transmission behaviour changes when the boundary varies, an appropriate measure has to be given. For this, the middle ear transfer function T_ME is used. As shown in (2), this is the quotient of the displacement of the umbo $\boldsymbol{u}_\mathrm{U}$ normal to the plane and the acoustical pressure p_U at this point

$$T_\mathrm{ME} = \frac{\boldsymbol{u}_\mathrm{U} \cdot \boldsymbol{n}}{p_\mathrm{U}}\,. \tag{2}$$

Further, the transfer functions for six cases are compared. First of all, an ear canal of 25 mm length, 7 mm in diameter with no vent is used as a reference case. As emphasised before, the insertion depth is then reduced to a remaining length of the meatus of respectively 15, 8 and 4 mm. For each length, a case with a small vent diameter of 1.5 mm and a bigger one of 2.5 mm are modelled. To illustrate this procedure, an example is shown in Fig. 3. The chosen angle of the eardrum is 55 °.

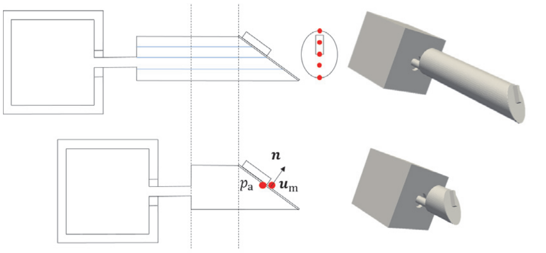

Figure 3: Upper panel: used monitoring trajectories to investigate transversal variations in sound pressure; Lower panel: example for modelling a deeper insertion depth

Results I: Displacement of Umbo

The TM and the ossicle chain are complex and have a large number of mechanical parameters, which are apriori unknown. As an example, the eardrum consists of parts with significant variation in stiffness. Hence, the mechanical properties vary vastly. Despite these considerations, various authors showed by means of Laser Doppler Vibrometry (LDV) that the movement of the stapes footplate $\mathbf{u}_\mathrm{S}$ is proportional to the displacement measured at the umbo $\mathbf{u}_\mathrm{U}$ e.g. [3, 4]. In short, this is an indicator that the information of the stapes acting on the fenestra ovalis, is already contained in the movement of the umbo (except for an offset). This assumption is revisited in the discussion. The simplified middle ear model, used here, is validated by comparing the displacement of the equivalent umbo point of the model eardrum to the findings from literature. The aim was to adapt the parameters of the model in such a way that the displacements are in range with the inter-individual differences of measured displacement from literature, which are represented by the grey area in Fig. 4. The frequency characteristics of the FE-model, shown by the blue line, is in good accordance with the mean behaviour of the measured data.

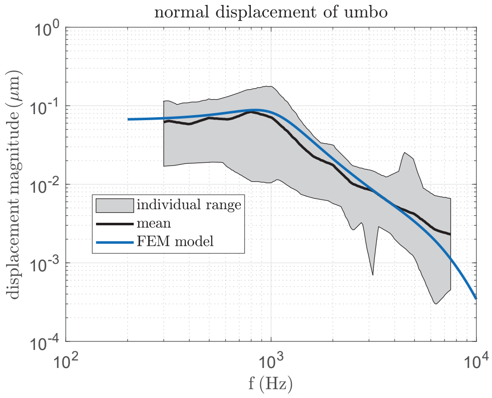

Figure 4: Normal mechanical displacement of the model umbo (blue line) at 80 dB SPL compared to interindividual data range (grey area) from literature and their mean (black line)

Results II: Transversal pressure distribution and variation of remaining length

In Fig. 5 the transversal variations of the reference case are depicted. Exemplarily, the curves for sound pressure level (SPL) over canal length for 5 and 10 kHz are shown. At the positions near the inner face of the mold, large variations are observed. The reason for these variations, which in the studied cases reached up to 29 dB, is the jump in acoustic impedance due to the different cross-sectional diameters of the excitation and the ear canal entrance. Following the trajectories further into the direction of the TM, the soundfield becomes homogeneous, and after an initial length of maximal 5 mm (considering all cases), no more deviations between the five monitoring lines can be seen. Generally, the deviations increase at higher frequencies. These findings are roughly consistent with [5], although Stinson and Daigle used a different set up, by means of a Zwislocki coupler and a different vent diameter. They found the initial length to be 4 mm and the maximal variations to be 20 dB at 8 kHz.
At the other termination end, first the mechanical displacement for the reference case at 10 kHz over the eardrum are shown in the left penal of Fig. 6. Directly in comparison, in the right penal, the SPL is displayed. Clearly, one can observe rather small differences for the acoustics compared to the complex displacement shape. Also, the change in SPL systematically increase from the top of the drum to the innermost point of the auditory canal. This leads to a simple explanation. The wave fronts, which are planar after the initial length, arrive at the top of the drum. Despite all mechanical movement, from there on the TM behaves like a continous canal

boundary. As the TM does not terminate the canal perpendicular, the tapering shape leads to an increase in SPL. So the critical factor for variations over the TM is not the mechanical behaviour, but the angle of the eardrum. For the investigated cases (all 55 °), maximal variations of 3 dB were found.

Moreover, the changes for simulating the increasing insertion depth of the mold are examined. Therefore, first the SPL at the umbo together with the transfer function for the reference case is shown. One the one hand, the typical 1/4 wavelength resonance in the SPL spectrum is visible. On the other hand, the transfer function shows no additional resonance in the associate frequency range. The transmission mainly has the same appearance as the rear displacements for a constant sound pressure over the TM, e.g. as it was the case for the validation of the middle ear model (Fig. 4). Clearly, this indicates a piston-like movement and the mode shape of the whole TM seems to have little impact on the actual displacement of the umbo. However, these findings change, when the differences for the six investigated cases are taken into account. Figure 7 summarises the representative results. The remaining lengths of 15, 8 and 4 mm are depicted in red, blue and green, respectively. The two vent cases are distinguished by the linestyle. Dotted lines represent the small vent diameter (1.5 mm) and solid lines are for the big vent cases (2.5 mm). First of all, a systematically increase of the lower frequency range is observed. In addition, at frequencies between 5 to 7 kHz, an increasing difference in the transmission behaviour occurs. These changes become larger than 5 dB when the remaining length decrease to less than 5 mm. A first reason for this difference in the transmission (ratio of umbo displacement to acoustic pressure at the umbo) is that for short remaining lengths, the transversal variations are higher due to the initial length (see findings for transversal variations). Nevertheless, also for cases where the remaining length is longer than the 5 mm after which the transversal variations are negligible, a change in the transfer characteristic can be observed. Hence, these differences can not be explained only by means of transversal variations. Here it is found that for frequencies higher than 7.5 kHz, wave effects occur not only over the canal length, but also over the cross sectional dimensions of the canal. These slightly change the mechanical motion patterns. Hence, variations of the middle ear transfer function for the umbo can be seen. Summarizing the information of Fig. 7, changes of boundaries lead to great differences in SPL. However, the transmission behaviour by means of the middle ear transfer function of the umbo, for the presented model is relatively robust. In the frequency range up to 5 kHz, the differences to the reference are negligible. After that, two prospects are possible. When the remaining length is longer than 5 mm, the transfer functions vary up to 2 dB. For deeper insertion depths, the variations increase up to 6 dB.

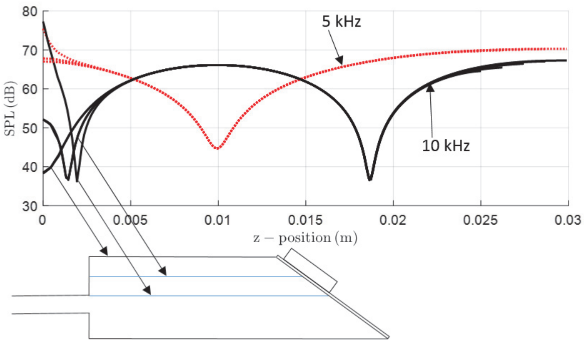

Figure 5: Plot of SPL on the medial monitoring points through the meatus of the reference case for 5 and 10 kHz

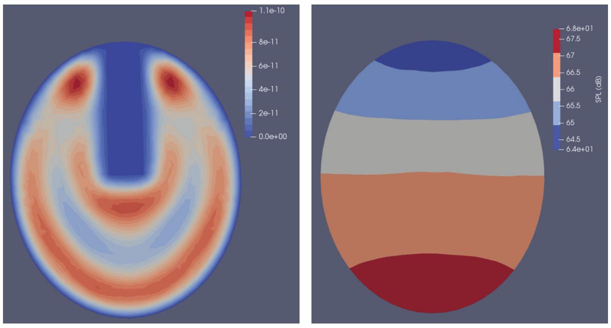

Figure 6: Transversal variations on the inner face of the model TM of the mechanical displacement (left) and SPL (right) at 10 kHz

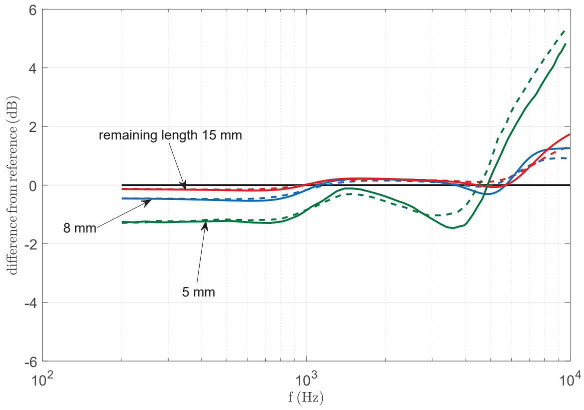

Figure 7: Difference to reference case of varied insertion depth and vent diameters (1.5 mm dotted lines; 2.5 mm solid lines)

Discussion

Based on the results, some basic assumptions which lead to essential simplifications of the model should be discussed. Primarily, the simplified middle ear model might be questionable. Clearly, it is known that for example the shape of the TM, which realistically would be conical, is not met by the model of a simple plate. Likewise, other deviations from exact morphological properties are obvious. Nevertheless, two findings support the validity of the model in terms of representing the true middle ear behaviour. On the one hand, it was shown that with the observed amplitudes of mechanical displacements, which are at least in the same scale as LDV measurements reveal, no major retroactive effects on the acoustics are observed. The critical factor despite the strongly inhomogeneous displacements over the TM is the angle of the eardrum, rather than any mechanical property. Therefore, the exact mechanical pattern is of minor interest. On the other hand, the transfer functions are rather insensitive for a wide frequency range (up to 7.5 kHz) to changes of the boundary. This indicates that up to these frequencies no significant changes of the mechanical behaviour occur. If larger variations had been found in the model, the question would arise whether a single point transfer function of the umbo is really an appropriate measure. In our results no such indication were found so far, and the validation of the model displacements are only done for the umbo.

Moreover, one main goal of this finite element study was to evaluate whether a characteristic transmission behaviour can be observed, even if the acoustic quantities change vastly. To this end, the 3D resolution of both the sound pressure and the displacements can be used to understand the basic interactions. It was found, that the impact of the 3D mechanisms on the umbo is minor up to frequencies of at least 7.5 kHz. So up to this frequencies, the REM are believed to be a precise measure for further sound perception. Within this range the well-known pure acoustic effects, such as probe tube placement difficulties due to standing wave minima over the medial length of the auditory meatus, are more crucial. At higher frequencies, the transmission behaviour is sensitive to changes of the boundary. The reasons of transversal wave effects and also the higher variations over the initial length (when considering a deep insertion depth) were already given before. Based on this, the validity of single point REM being representative for further sound transmission and perception at frequencies higher than 7.5 kHz is questionable. These findings are in good accordance with conclusions of detailed 3D holographic studies on the movement of the tympanic membrane [4].

Conclusion and Outlook

In this study, a 3D finite element model considering both the acoustic properties of the auditory canal (a simple cylindrical model), as well as the movement of the eardrum, is presented. Partly occluded ear canals, as they are prominent e.g. for the usage of hearing aid otoplastics, and an optional venting were modelled. Based on results from literature, the displacements of the umbo point is assumed to determine the further transmission to the inner ear. The simplified middle ear model was found to be in good accordance with the measured frequency behaviour of the umbo displacement. Additionally, the 3D movement over the cross-sectional area of the TM showed strongly inhomogeneous patterns and high frequency dependency. Nevertheless, the variations of the acoustic SPL are in the range of 3 dB. The eardrum angle is the critical parameter here (only one angle is considered here). On the inner face of the mold, up to 5 mm (initial length) depth in the meatus, very large transversal variations of SPL occur in the model (max 29 dB for the studied cases). After the initial length, the sound field becomes one-dimensional by means of plane wave fronts, until reaching the top of the drum (point where eardrum starts and due to the angle, the canal is tapered). Further, the transmission behaviour by means of the middle ear transfer function T_{ME} was investigated. Concerning this, differences in T_{ME}, while changing the boundaries were monitored. Representatively, here changes in boundaries were modelled by shortening the remaining length of the auditory canal, hence modelling an increasing insertion depth of an otoplastic. The reference case is the longest un-vented case of 25 mm length and 7 mm in diameter. The results show an increase of differences in the transfer function at frequencies higher than 5 kHz. For remaining lengths of bigger than 5 mm, the differences stay smaller than 2 dB up to 10 kHz. When the remaining length is smaller than 5 mm, the large transversal variations due to the initial length lead to differences of up to 6 dB. At frequencies higher than 7.5 kHz additionally, the umbo displacements are influenced by transversal wave effects over the cross-sectional area, as the characteristic measures of the model then come into the range of the wavelength. In summary, based on the model, REM as pure acoustic quantity is rated as a valid measure for the transmission behaviour up to 7.5 kHz. After that, differences in the transfer functions indicates a more complex behaviour. Also, when the remaining length is shorter than 5 mm, further attention should be paid.

Additional research needs to be done to quantify the transversal wave effects at higher frequencies. Also, the results should be validated for more realistic ear canal geometries and by means of measurements.

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