Modeling the sound field in front of the human eardrum for hearing aid applications

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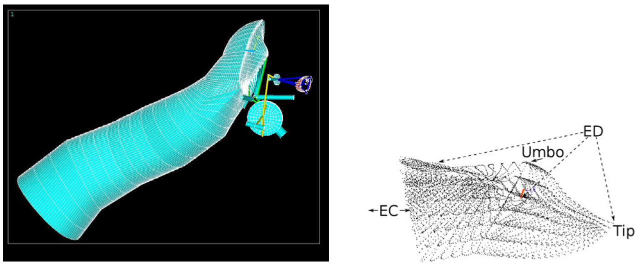
Introduction

The sound pressure at the eardrum (ED) is a reference quantity not only in hearing aids but in virtually all applications involving sound delivery to the ear, such as mobile phones, ear- and headphones. As the direct measurement of the ED pressure p_D is too elaborate and sensible to positioning errors, it must be predicted in some way. One question arising within this context is, whether probe tube measurements can be taken as reference. Most attempts in ear canal (EC) modeling exclude detailed information about the vibrating ED from their analyses. Given in [4], a derived theoretical 1-dimensional model holds as long there're no significant ED vibrations, i.e. they're small compared to air vibrations in some distance to it [2]. An anlaysis of the vibrating ED and its influence on the sound field in the EC should bring further knowledge. In this paper, a finite element (FE) model comprising a detailed representation of the vibrating ED while preserving enough flexibility to be applied to a number of in vitro and in vivo human specimen is presented and validated. Detailed information can be found in [3]. Respective data were gathered at the MHH on temporal bones as geometry scans of the EC mold and laser Doppler vibrometry (LDV) scans of their related ED. The main focus of this work is on hearing aid applications with a frequency range of $f = 0.1 \ldots 10$ kHz and a required level tolerance of $\Delta L \pm 5$ dB.

FE-Model

To validate the subsequently presented method a FE-Model of the human EC, ED, middle ear (ME), and cochlea, proposed by [1], as shown in figure 1(a) was used. In the following this model is referred to as *reference model* (REFmod). First of all solutions for pressure $p_{\mathrm{REFmod}}(f)$ and ED displacments $u_{\mathrm{REFmod}}(f)$ were gained for a frequency range of $f = 0.2 \ldots 10$ kHz in steps of $\Delta f = 200$Hz. Outcomes of the calculations are shown as boxplots of pressure $p(f)$ over the region in front of the ED, figure 1(b), relative to a given reference pressure. Thus, the numerical solution is not only represented at given points but through a complete statistic over about 6000 nodes inside this region. All FE calculations were done with the software Ansys$^{\mathrm{TM}}$.



(a) (b)

Figure 1: (a) Complete FE-Model including the middle ear and cochlea provided by [1]. This model is referred to as *reference model* REFmod. (b) Plot of all nodes used for showing the solutions of pressure $p(f)$ in front of the ED.

Modeling the ED

To analyze the influence of individual ED vibrations on the sound field in front of it, a FE model should not require the mechanical properties of the ED, ME, and cochlea be modeled individually. Instead, a method is introduced with which the displacements $u_{\mathrm{REFmod}}(f)$ of the reference model are represented by amplitude and phase and applied on the ED as boundary conditions, modeling it as a velocity source as shown in figure 2(a). This source superposes with the pressure source p_0 at the EC entrance. With such a model the individual ED vibrations can be, for example, described through LDV measurements of the specimen. This reduced model is referred to as the *ear canal model* (ECmod) to distinguish from the *reference model* Refmod.

First, this solution $p(f)_{\mathrm{ECmod}}$ is compared to $p(f)_{\mathrm{REFmod}}$, figure 2(b). Obviously, the absolute error is less than 1 dB up to 10kHz with a negligible variance. Therefore, it appears that this method resembles the reference model appropriatley and can be used to evaluate different test cases.

Calculation of the ED pressure

To validate the influence of the vibrating ED, different computations have been carried out. Some of those are discussed in the following subsections. The solutions for each test case are shown relative to the, previously described, ECmod for evaluation over the region shown in figure 1(b).

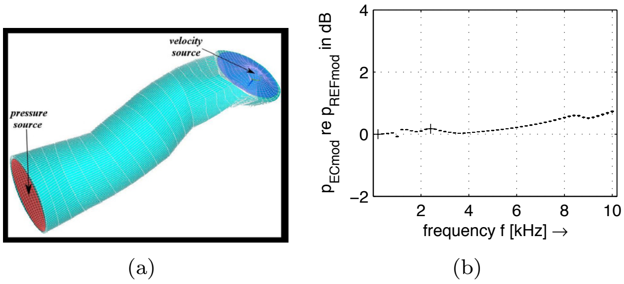


Figure 2: (a) Modeling situation of the *ear canal model* ECmod. The pressure source p_0 at the EC entrance superposes with the ED modeled as a velocity source. (b) Solution of pressure $p_{\mathrm{ECmod}}(f)$ of the *ear canal model* relativ to $p_{\mathrm{REFmod}}(f)$ of the *reference model*.

Reduced effective ED area

In figure 3(a), the effective vibrating ED area was reduced to about one third centered around the Umbo. The dotted line around this area marks the border of the model ED. All remaining ED nodes were modeled rigid, i.e. displacments were set to $u = 0$. This represents the case when LDV data are used to model ED vibrations as due to the EC curvature just a part of the ED can be "seen" by the laser. Figure 3(b) shows the results compared to $p_{\mathrm{ECmod}}(f)$. The overall pressure deviation is less than about 1-2 dB and is therefore negligible.

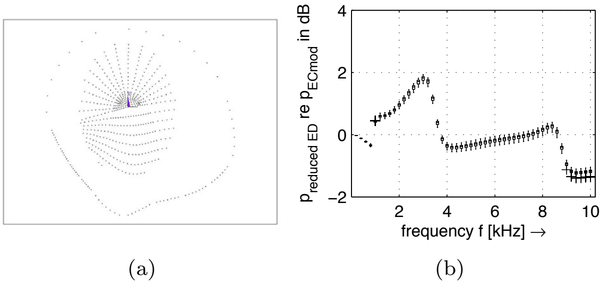


Figure 3: The effective ED area (a) was reduced to one third and (b) the results compared to $p_{\mathrm{ECmod}}(f)$.

Influence of the vibrating eardrum

Another point of investigation was the influence of the ED vibrations alone, i.e. without a source p_0 acting on the EC entrance as pictured in figure 4(a). The results were shown in figure 4(b).

Above $f \approx 4$ kHz the results for the rigid ED and the ECmod are almost the same. Just for lower frequencies a deviation is noticeable. The ED alone approximates those two curves at both EC resonances but its influence on the sound field in front of the ED seems to be very small.

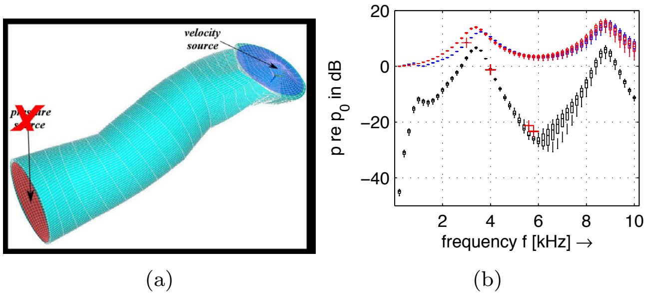


Figure 4: (a) EC model with pressure source disabled (p_0 off), (b) Solutions for: *red (upper) curve*: ED modeled rigid, *blue (middle) curve*: $p_{ECmod}(f)$ of ear canal model, *black (lower) curve*: influence due to ED vibration alone

Difference of eardrum vibrations in non-normal direction relativ to the ECmod

Measured LDV data give just information in the lasers viewing direction. When those data were applied on a model ED corrections in normal directions should be applied. As depicted in figure 5 a simplified planar ED vibrates in three dimensions inside its coordinate system CS_1. The measured displacements $u_{z'}(f) = [u_x(f), u_y(f), u_z(f)]^T$ could be interpreted as the "viewing direction" of the laser inside its own CS_2. In this example the difference between both quantities is an angle correction factor $1/\cos\alpha$ which depends on the relative position of both coordinate systems. Two error sources arise in this procedure: an *amplitude and phase* and a *direction correction* error. The first error is due to the fact that just the combined displacement magnitude $|u_{z'}(f)|$ is measured and therefore even no detailed phase information of each component. So it has to be assumed that the main information lies in $u_{z'}(f)$. The second error depends on the quality of mapping the LDV data on the model ED. Since there are in general much less LDV data points than mesh nodes on the ED interpolation is necessary, too.

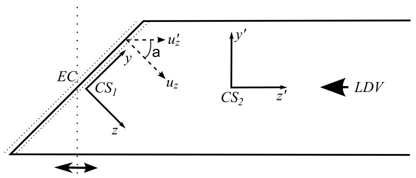


Figure 5: Virtual laser viewing direction used to model 3-dimensional ED displacements $u_{\mathrm{ECmod}}(f)$. The displacements $u_{z'}(f)$ are those measured by the laser. The x-axis is normal to this paper.

To estimate the overall error the displacements $u_{z'}(f)$ were calculated and applied to the ED with the angle correction factor taken into account. As the model ED is no planar surface this angle correction therm isn't correct for all ED elements. So both error sources mentioned contribute to the results which are shown as $p_{\mathrm{ldv}}(f)$ relative to p_{ECmod} in figure 6. As the overall deviation is less than 1 dB it seems that missing information about the exact ED vibration isn't important and can be well defined through LDV data.

Calibration error

Even if deviations of pressure $p_D(f)$ in front of the ED in the previously described calculations are small the method using the ear canal model ECmod is only valid

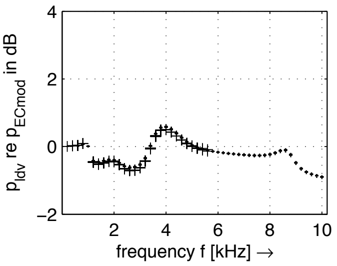
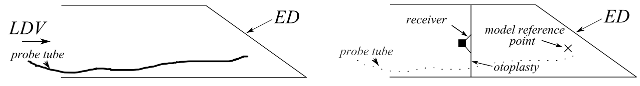


Figure 6: Solution for pressure $p_{\mathrm{ldv}}(f)$ for "laser" displacements $u_{z'}(f)$, see figure 5, relative to p_{ECmod}.

if the simulated pressure excitation leads to the same sound field as in measurement set-up. So it must be examined what the magnitude of the expected deviation due to calibration mismatch is. This situation is shown in figures 7(a) and 7(b).



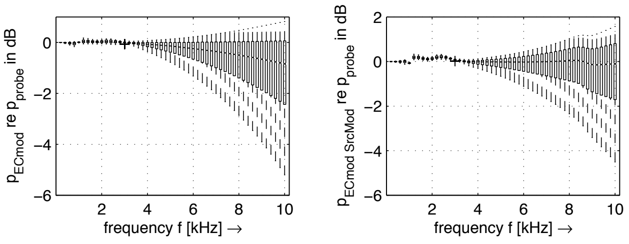
(a) open model (b) closed model

Figure 7: Set-up for measurement and simulation situation. (a) Open model during measurement with no shell placed inside the EC, (b) closed model during simulation with a shell

Figure 7(a) shows the measurement set-up. Depicted is a simplified EC without a shell inside (*open* model). The laser scans the ED which is excited by a loudspeaker outside the EC while a probe tube measures the pressure $p_D(f)$ in front of the ED as the reference quantity. In figure 7(b) the situation is similar for the ECmod with a shell placed inside (*closed* model). To compare the solutions of the closed model with the measurements of the open model a reference point inside the ECmod has to be chosen. At this point a deviation occurs caused by two facts:

1. The *exact position* of the probe tube position in measurement set-up is not known. Therefor a virtual reference point inside the model must be chosen as close as possible to this point.
2. The *sources* in measurement and simulation are different.

In both cases plane waves can be expected which differ in amplitude and phase. Therefore, a pressure difference $\Delta p(f)$ between both set-ups occurs. So it should be tested what the maximum deviation of the pressure in front of the ED relative to a given probe tube reference point is. This is shown in figure 8(a). The deviation is within the postulated tolerance of ±5 dB for all points and frequencies.



(a) pressure source p_0 (b) pressure source $p_{0,\mathrm{ScrMod}}$

Figure 8: Level difference due to calibration mismatch. (a) Model ECmod relative to a probe tube reference point in front of the eardrum, (b) same situation with a modified source at the ear canal entrance.

As the boxes mark the quantile $p_{0.25}$ and $p_{0.75}$ for fifty percent of all cases the pressure deviation is less than 3 dB up to 10 kHz. Figure 8(b) shows the same model but with a modified source

$$p_{0,\mathrm{ScrMod}}(f) = p_0 \cdot \max\{\Delta p(f)\}$$

at the EC entrance while the ED vibrations are the same as in figure 8(a). So the source $p_{o,\mathrm{SrcMod}}$ does not relate to the modeled ED vibrations, differing in amplitude and phase. This complies the situation presented in figures 7(a) and 7(b). As can be seen the deviations remain similar with just a small offset. Finally the error due to calibration lies within the postulated tolerance of $\Delta\ L\ \pm\ 5$ dB and the ECmod method can be considered as valid.

Conclusions

The investigations show that the ED has only little effect on the sound field inside the EC. The biggest deviation is caused through calibration because of different source excitation in measurement and simulation. The positioning error of the probe tube has a similar effect. Despite these errors, the LDV data can be used as source quantity to be applied on the ED with a sufficient accuracy at least for the model studied here.

As those results where just gathered with one FE model it must be validated with at least one more model. Therefore, in a next step, we plan to apply the methodology presented here to a temporal bone with large ED vibrations.

Acknowledgement

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