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Prediction of the sound pressure at the ear drum for open fittings

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The fitting of hearing aids requires knowledge of the sound pressure generated at the ear drum. Traditionally, the sound pressure at the ear drum is estimated by the use of a model of an average ear canal (e.g. a coupler), but obviously, such a model cannot account for inter-individual differences. A better practice, but difficult, is the measurement at the ear drum with a probe-microphone. Alternatively, the sound pressure at the ear drum can be predicted by measurements away from the ear drum. Two methods, one of them based on the phase of the reflectance, measured at the ear mold, and the other one based on minima of the sound pressure, measured in the ear canal a few millimeters away from the ear mold, were investigated for the use with vented hearing aids. The methods to predict the sound pressure at the ear drum for vented hearing aids will be presented. A preliminary validation by probe tube measurements in 28 ears shows that the accuracy of the predictions is close to what could be obtained with closed fittings (Sankowsky-Rothe et al. 2011), with a few exceptions that will be discussed.

1 Introduction

In a previous investigation [1], the sound pressure at the ear drum was predicted for closed hearing aid fittings, using two methods, both based on measurements away from the ear drum. Based on comparisons with probe tube measurements at the ear drum, it could be shown that those methods allow predictions with an acceptable accuracy, clearly outperforming non-individual prediction methods by ear simulators. However, in hearing aid fitting it is desirable to occlude the ear as little as possible, if hearing aid gain permits. Mild to moderate hearing losses are usually fitted with vented or open hearing aids. In the following, the influence of vents in ear molds on the prediction methods will be investigated.

2 Materials and methods

As in [1], two methods for the prediction of the sound pressure $\underline{\hat{p}}_d$ at the ear drum are investigated, with different application scenarios:

- a method using independent models of source and ear,
- a method using one joint model of source and ear.

Both methods use the model framework depicted in figure 1. The source is characterized by its source volume velocity $\underline{\hat{q}}_s$, its source impedance $\underline{Z}_s$ and the source voltage $\underline{\hat{v}}_s$. The vent is represented by the vent impedance $\underline{Z}_v$. The ear canal is modeled by the transfer parameters $\underline{e}_{ij}$ and $\underline{Z}_l$ which is the load impedance terminating the ear canal. $\underline{\hat{p}}_{ec}$ is the sound pressure at the inner face of the ear mold.

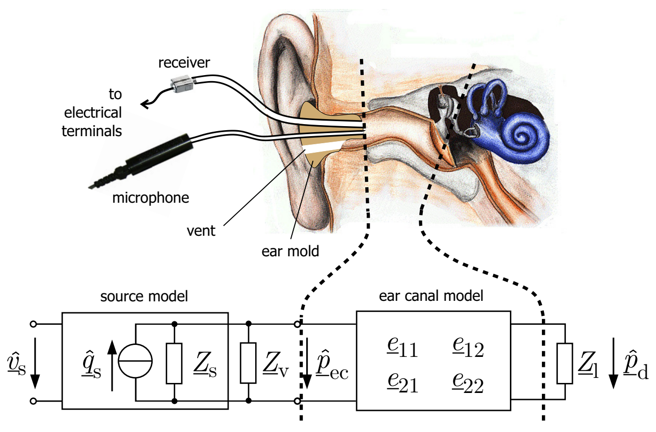

Figure 1: Model framework for the prediction of the sound pressure $\underline{\hat{p}}_d$ at the drum, in ear canals with vented ear molds. $\underline{\hat{v}}_s$ is the source voltage, $\underline{Z}_v$ is the acoustic vent impedance, $\underline{\hat{p}}_{ec}$ is the sound pressure at the inner face of the ear mold, $\underline{\hat{q}}_s$ is the source volume velocity, $\underline{Z}_s$ the acoustic source impedance, $\underline{e}_{ij}$ the transfer parameters of the ear canal model and $\underline{Z}_l$ the acoustic load impedance. The drawing of the ear was adopted with kind permission from ars auditus (www.ars-auditus.de).

2.1 Method using independent models of the source and the ear

In this method, the source is characterized by its Norton equivalent. The two source parameters, i.e. the volume velocity $\underline{\hat{q}}_s$ (relative to the source voltage $\underline{\hat{v}}_s$) and the source impedance $\underline{Z}_s$, are determined from measurements in which the source is connected to four different acoustic load impedances. Detailed information about this procedure are given in [2, 1].

The model of the ear is based on the acoustic impedance, measured at the inner face of the ear mold. This model includes both, the ear canal and the acoustic load which, at low frequencies, reflects the impedance of the ear drum and that of the vent. The challenge, which is new compared to the procedure in [1, 2], now is the prediction of the influence of the vent on the measured impedance.

The first step in the modified algorithm for the estimation of the ear canal model is a rough estimate of the canal modeled as a conical tube terminated by an average ear drum impedance according to [3]. The conical tube is represented by its length l_{ec} and the radii r_{ec} (at ear mold) and r_d (at the drum). The first two parameters were fitted by a nonlinear optimization with the simplex-algorithm (implemented using Matlab's `fminsearch` function). The third parameter has a fix value of 2.5 mm. The cost function used in the optimization was chosen to be

$$M_{ec} = \sum_{f=2\mathrm{kHz}}^{f_{min}\cdot 1,1} \left| \frac{\log_{10}\left|\underline{Z}_{cone}\right| - \log_{10}\left|\underline{Z}_{ec,m}\right|}{\log_{10}\left|\underline{Z}_{ec,m}\right|} \right|, \qquad (1)$$

with the impedance of the model $\underline{Z}_{cone}$ and the measured impedance $\underline{Z}_{ec,m}$. As can be seen, only frequencies from 2 kHz up to 1.1 times f_{min} (which is the frequency of the first impedance minimum above 2 kHz) are considered.

In the second step of the algorithm, a model of the vent is estimated. The model is defined by the three parameters length l_v, radius r_v and a factor g_v for the real part of the propagation constant γ. The impedance of the vent model is determined by sound propagation in a tube according to [4], with a radiation impedance of

$$\underline{Z}_{vR} = \frac{\rho c}{\pi r_v^2}\left(\frac{r_v^2 k^2}{4} + 0,6\,\mathrm{j}\,r_v k\right). \qquad (2)$$

Here, ρ is the density of air, c the speed of sound and k the wavenumber. The vent parameters are again estimated using the simplex algorithm. The required cost function was determined by visual comparison of impedance measurements of open fittings with simulations of different vent models and with measured impedances of occluded ear canals. The cost function finally adopted is

$$M_{\mathrm{v}} = \sum_{f=\min(f)}^{800\mathrm{Hz}} M_l \log_{10} \left| f \underline{Z}_{\mathrm{cone}} \right| + \sum_{f=0.9 f_{\min}}^{\max(f)} M_u \log_{10} \left| f \underline{Z}_{\mathrm{cone}} \right|, \tag{3}$$

with

$$M_l = \frac{500}{f} \left(\frac{1}{\pi} \left| \arg\{\underline{Z}'_{\mathrm{ec,m}}\} - \arg\{\underline{Z}_{\mathrm{ec,p}}\} \right| + \left| \log_{10}\left|\underline{Z}'_{\mathrm{ec,m}}\right| - \log_{10}\left|\underline{Z}_{\mathrm{ec,p}}\right| \right| \right), \tag{4}$$

and

$$M_u = \left(\left(\left|\underline{R}'_{\mathrm{ec,m}}\right| - \left|\underline{R}_{\mathrm{ec,p}}\right| \right)^2 + \frac{1}{2\pi} \left| \arg_u\{\underline{R}'_{\mathrm{ec,m}}\} - \arg_u\{\underline{R}_{\mathrm{ec,p}}\} \right| \right). \tag{5}$$

Here, single quotation marks (at the measured impedance $\underline{Z}'_{\mathrm{ec,m}}$ and reflectance $\underline{R}'_{\mathrm{ec,m}}$) indicate smoothed quantities. The smoothing of the impedance is realized by convolution with a normalized rectangular window of 50 points in the frequency domain. The smoothed reflectance is then calculated from the smoothed impedance. The subscript p denotes predicted quantities, i.e.

$$\underline{Z}_{\mathrm{ec,p}} = \left(\frac{1}{\underline{Z}_{\mathrm{cone}}} + \frac{1}{\underline{Z}_{\mathrm{vent}}} \right)^{-1} \quad \text{and} \quad \underline{R}_{\mathrm{ec,p}} = \frac{\underline{Z}_{\mathrm{ec,p}} - Z_\omega}{\underline{Z}_{\mathrm{ec,p}} + Z_\omega}, \tag{6}$$

with $Z_\omega = \rho c/(0.035^2 m^2 \pi)$ being the wave impedance. The initial values of the parameters of the vent model for the optimization were chosen to be

$$l_{\mathrm{v},0} = 0.02\mathrm{m} \tag{7}$$

$$r_{\mathrm{v},0} = \sqrt{\frac{2\pi 100\ \mathrm{Hz}\ \rho l_{\mathrm{v},0}}{\Im\left\{\underline{Z}'_{\mathrm{ec,m}}(100Hz)\right\}\pi}} \tag{8}$$

$$g_{\mathrm{v},0} = 7 \tag{9}$$

where $\Im\{\cdot\}$ is the imaginary part.

Once the vent model is optimized, the last step is the estimation of the ear canal model. The only difference to the estimation of the ear canal model for closed fittings described in [2] is that the reflectance of the model $\underline{R}_{\mathrm{model}}$ which is used in the cost function now includes both the ear canal and the vent model,

$$\underline{R}_{\mathrm{model}} = \frac{\left(\frac{1}{\underline{Z}_{\mathrm{ec,model}}} + \frac{1}{\underline{Z}_{\mathrm{vent}}} \right)^{-1} - Z_\omega}{\left(\frac{1}{\underline{Z}_{\mathrm{ec,model}}} + \frac{1}{\underline{Z}_{\mathrm{vent}}} \right)^{-1} + Z_\omega}. \tag{10}$$

2.2 Method using one joint model of the source and the ear

The joint modeling of the source and the ear is done as described in [1]: Briefly, the source is now characterized by the sound pressure relative to the source voltage $\hat{\underline{p}}_{\mathrm{ec}}/\hat{\underline{v}}_{\mathrm{s}}$, measured in the ear canal at about 5 mm away from the inner face of the ear mold. The part of the model representing the ear canal is then calculated from the minima of the measured sound pressure. The ear drum is assumed to be purely resistive, with the resistance being adjusted by requiring the sound pressure at the ear drum to be a smooth function of frequency.

2.3 Subjects

In this study sound pressure predictions are validated by probe tube measurements in 28 ears of 15 subjects. Depending on the size of the individual ear canal, the ear molds were produced with vents of 3 mm or 4 mm diameter. As an indicator for the anatomic variability of the ear canals, the main diameters of the cross section of the ear molds in the first bend were determined. In figure 2 these diameters are shown as black dots. For comparison, the gray dots show according data from previous studies [5, 1, 6]. As can be seen, the anatomic spread covers small- to medium-sized ear canals only.

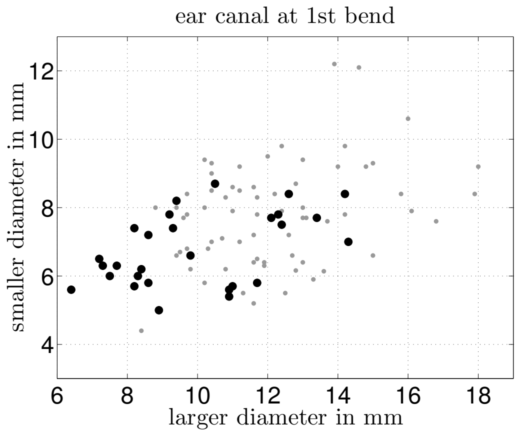

Figure 2: Diameters of the ear canals at the first bend, measured on the ear molds. The black points are data of the present study, the gray points are data from previous studies [5, 1, 6].

3 Results

The measured sound pressure at the ear drum relative to the source voltage of the 28 ears is shown in figure 3. At low frequencies up to about 1 kHz, the typical vent loss in sound pressure can be seen. At higher frequencies, 5…6 damped peaks and dips occur. They reflect the characteristics of the source (receiver and tubing) and its interaction with the individual ear. Below about 300 Hz, there is much noise in some measurements, due to the low magnitude of the sound pressure in this frequency region.

Regarding inter-individual variability, one notes a more or less constant spread of about 25 dB below 400 Hz...500 Hz. At 1 kHz on the other hand, the inter-individual differences become comparatively small (about 12 dB). In the frequency range from 1.5 kHz...5 kHz, they remain again rather constant at about 18 dB before increasing towards still higher frequencies. At 10 kHz, they become as lage as 38 dB.

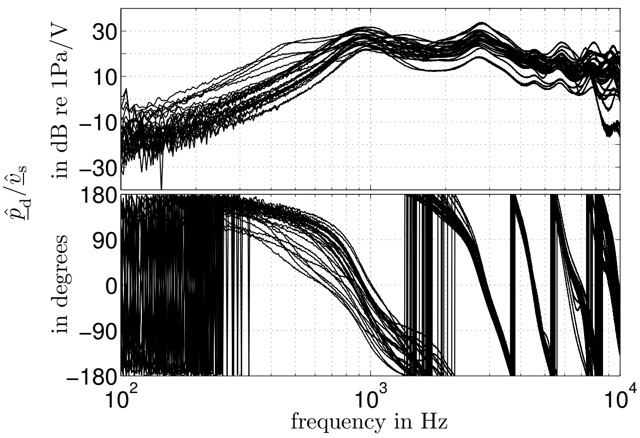

Figure 3: Sound pressure relative to the source voltage measured at the ear drum for the 28 ears.

In figure 4, the difference (in level and phase) of the predicted sound pressure at the ear drum with respect to the probe tube measurements is shown for the 28 ears. Besides the two prediction methods discussed above, an average model based on the numerical simulation of an ear simulator is included as well.

It can be seen that both individual prediction methods discussed here permit a better estimation of the sound pressure at the drum than the model based on the ear simulator, in particular at low and mid frequencies.

In general, the deviations between prediction and measurement are largest below 300 Hz, partly because of the noisy reference measurement, but also due to the problem of correctly estimating the vent loss (method using independent models) or even the inability to take vent loss into account at all (ear simulator). At slightly higher frequencies (400 Hz...500 Hz) the method using independent models tends to a small over-, the method using joint models to a small under-estimation, whereas the ear simulator still fails completely.

In the middle frequency range up to 6 kHz, predictions by both individual methods are quite good: the desired accuracy of ±5 dB is rarely exceeded (only around 5kHz, and just a little bit). While the ear simulator now doesn't seem to produce large bias any more, the random errors are clearly higher than those obtained using the two individual methods.

At higher frequencies (above say, 6 kHz) there is only a small benefit in using the individual models compared to the ear simulator.

There is one prediction of the method using independent models where the sound pressure is extremely underestimated. In this case the measured impedance was already suspicious, but it was nonetheless retained. For a clinical application, such suspicious measurements should be signaled, in order to avoid largely wrong predictions.

The phase deviations for method using independent models are mostly less than 30° except for frequencies higher than 8 kHz. For the method using one joint model, the deviations exceed 30° at 5.5 kHz. The prediction with the ear simulator results in large phase deviations except for a frequency range of about 2.5 kHz...6 kHz.

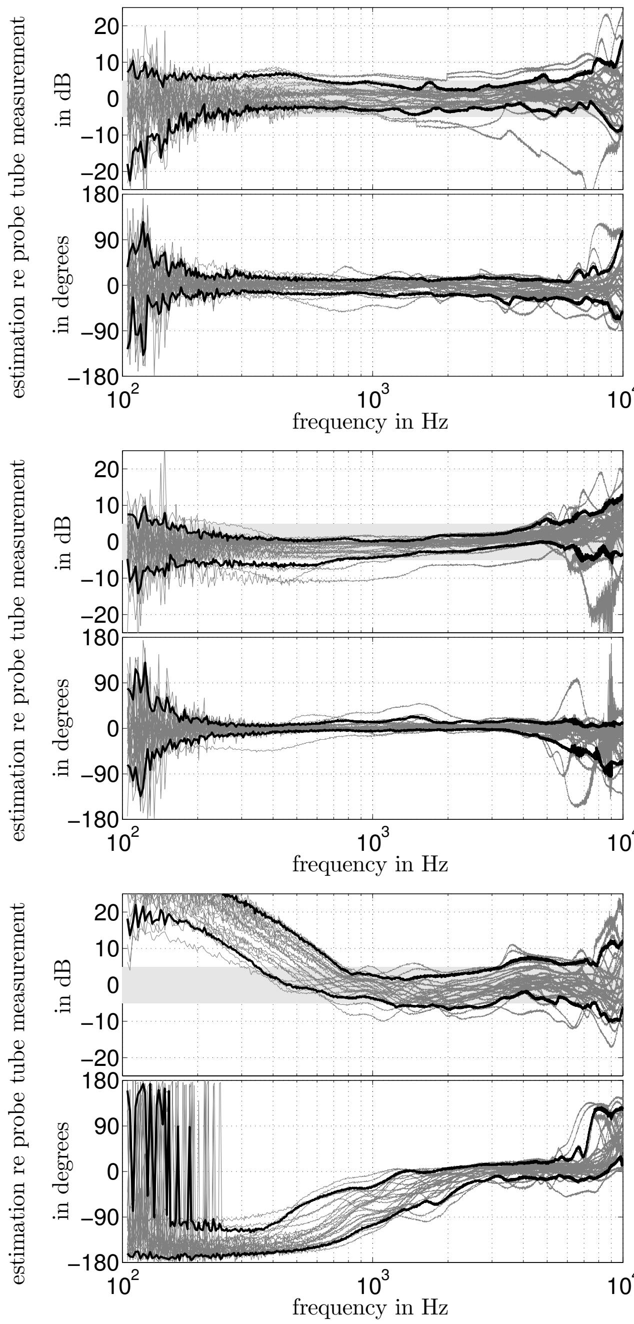

Figure 4: Level and phase differences of the predicted relative to the measured sound pressure at the ear drum. **Top:** method using independent models, **middle:** method using joint models, **bottom:** ear simulator model. The gray lines are the individual data, the black lines give the 10th and the 90th percentile.

4 Discussion

4.1 Comparison of the two individual prediction methods

Both individual prediction methods lead to a much better agreement with the measured sound pressure than the ear simulator model. The method using one joint model seems to be slightly better than the method using independent models, which was already observed in occluded ears in [1]. This is plausible because the former needs several measurements (one on the ear and six on the source) and the modeling approach is more elaborate compared to the method using one joint model. However, the method using independent models offers an advantage in hearing aid fitting in that only one measurement on the patient's ear is necessary. The optimization of the hearing aid coan then be done independently, without additional measurements on the patient. In contrast, the method using one joint model would require one measurement on the patient's ear for every modification of the hearing aid.

4.2 Comparison to predictions in occluded ears

The accuracy of the predictions in vented aids reported on here is comparable to that obtained in occluded ears (see [1]) for frequencies up to about 5 kHz. At higher frequencies, the prediction appears to be more accurate in occluded ears. At this point, we do not have an explanation why the accuracy of the predictions in the open ears isn't as good in this frequency range *regardless of the modeling method* (independent or joint modeling).

If only the method using independent models is regarded, one may note that, besides the well known influence of the vent on the sound pressure for frequencies below 1.5 kHz, in many cases there is also an influence at high frequencies above approximately 6 kHz (which was also found in [7]). An example of this influence is given in figure 5: In the upper graph, impedances of a vent model (dashed, light gray line), of an occluded ear canal model (dark gray, dashed-doted line), and the corresponding measured impedance of one vented ear (black, straight line) are shown. As the vent acts as a wave guide, its impedance will exhibit a minimum at high frequencies which, depending on the length of the vent, may occur within the frequency range considered here (below 10 kHz). In figure 5, this minimum can be seen at around 8.4 kHz. A wrong estimation of the vent parameters (or an inappropriate model structure) will influence both the estimation of the ear canal model and in addition the prediction of the sound pressure at the drum in this frequency region.

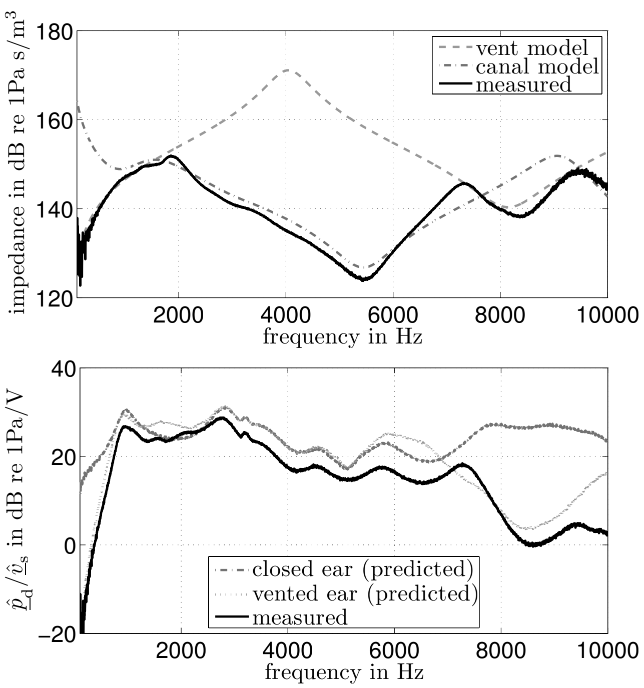

Figure 5: Example for the influence of the vent on the impedance and the sound pressure. On top, impedances of a vent model, of an occluded ear canal model, and the corresponding measured impedance of a vented ear. Below, transfer functions of sound pressure relative to the source voltage for a prediction of the occluded ear, a prediction of the vented ear and the measured transfer function.

In the lower graph of figure 5, there are transfer functions of the sound pressure relative to the source voltage. There is a transfer function for a prediction of the closed ear (dark gray, dashed-doted line), a prediction of the vented ear (light gray, doted line) and another one measured on the vented ear (black, straight line). It can be seen that there is also a minimum at 8.4 kHz only in the vented transfer functions.

For the method using one joint model, this effect should not play a role. The vent minimum may however interfere with the identification of the minimum associated with reflections from the ear drum, although this will happen extremely rarely as the two minima are usually well separated (the latter being at around 5.5 kHz in figure 5).

5 Summary and conclusion

In this work, we extended our method of independent models of source and ear to the prediction the sound pressure at the ear drum in vented ears. This method and another prediction method based on the minima of the sound pressure measured in the ear canal (where source and ear are modeled jointly) were compared to probe tube measurements. Both individual prediction methods showed a much better agreement between predicted and measured sound pressure than a prediction with an ear simulator. At frequencies above 6 kHz, there is only a small benefit in using the individual predictions, which is slightly higher for the phase than for the sound pressure level.

Further work is necessary to identifiy the source of a diminished accuracy at very high frequencies above 6 kHz.

Acknowledgements

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