Measurement of equal-loudness contours using eardrum pressure as reference signal

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Equal-loudness contours represent the relationship of loudness perception and sound pressure at the ear. Usually, the reference pressure is defined by a standardized calibration procedure. Individual ear canal characteristics significantly influence the contours, resulting in peaks and notches. By choosing the eardrum pressure as reference for perception measurements, individual ear canal features are cancelled, when loudness and pressure are related. Thus, flatter contours can be achieved.

Finite-element simulations of the sound field in the canal have shown that signals at remote positions may differ significantly from the eardrum pressure. Thus, to achieve eardrum related measurements, it is necessary to insert probe microphones sufficiently deep into the canal. The desired signal has to be estimated from a distance, since measurements directly at the drum are not practical. Thus, the transfer function to the drum must be calculated.

In this contribution, a new audiometric method with reference to a precisely estimated eardrum pressure is shown. The positioning, estimation and transformation processes are verified by finite-element models and experiments with an artificial ear. The results of a preliminary equal-loudness contour measurement are presented.

1   Introduction

Loudness is a function of frequency and of the sound pressure at the ear. Equal-loudness contours are graphs in a pressure-over-frequency diagram denoting the same perceived loudness. They can be recorded by measuring points of subjective equality (PSE) of test sounds and reference signals. It is common practice to choose the free field sound pressure found at the subject's head position as reference for loudness PSE measurements. Thus, the results depend on the individual head and ear canal geometry. Due to the duct-like structure of the canal and its almost rigid termination, its transfer function and hence the equal-loudness contours exhibit significant peaks and notches. For different individual ear canal geometries, the structure of the contours varies significantly. Thus, averaged contours are usually blurred and show broad extremal values. Using the eardrum pressure as reference signal improves measurements at the ear essentially. Measurement results are independent of individual ear canal geometries. Thus, results gathered from different subjects are better comparable. In addition, the spectra of pressure signals at the drum (and, consequently, the equal-loudness contours) are flat in comparison to other signals in the canal. As they are measured near an almost rigid surface, no quarter-wavelength minima occur. Procedures for eardrum pressure estimation by external measurements are described by various authors ([1], [2] e.g.). Here, the desired pressure is calculated by transforming signals from the measurement point to the eardrum by using a cylindrical model of the residual ear canal. The transformation length is estimated by evaluation of the first minimum of the sound pressure, which is a quarter-wavelength minimum. At high frequencies, however, significant errors are observed. A method developed by one of the authors takes the input impedance of the ear canal into account [3]. After the ear canal geometry is estimated from the impedance function, a two-port model of the canal is established. While the method provides good results for evaluation data from model canals, it fails for some natural ear canal geometries.

The method described in this contribution yields accurate results even for higher frequencies, as the least two minima are taken into account. Further, a flexible model of the sound field in the residual canal is applied. It turned out that only one probe microphone and only a pressure measurement is necessary to achieve significant results. After the method is described in detail, verification experiments with a finite-element model and an artificial external ear are displayed. To document the first audiometric results, pilot equal-loudness contour measurements with reference to the eardrum pressure are presented.

2   Estimation method

2.1   The eardrum sound pressure and the sound field in the canal

The eardrum sound pressure, as referred to in this text, is defined as the maximum sound pressure occurring at the drum. For most frequencies in the hearing range, this pressure can be found at the innermost point of the ear canal, in the angle between canal and drum, although for some frequencies around the middle ear resonance, the maximum location is shifted away from the innermost point. As the wavelength of sound at those frequencies is considerably larger than the displacement of the maximum, no essential error occurs. The innermost ear canal point can be regarded as reflection point of the wave or as rigid termination of the canal, thus, the point is denoted T and the eardrum signal is subscripted p_T.

The direct measurement of p_T is not easily performed. In practice, probe microphones are inserted into the canal to gain an approximation of p_T. To prevent eardrum damage, the probe tips have to stay sufficiently far away from the drum. The probe microphone signal p_M consequently differs from p_T by the primarily unknown microphone-to-drum transfer function $H_{MT} = p_T / p_M$. Depending on the insertion depth, significant errors arise. Thus, the transfer function H_{MT} has to be estimated using data from the remote measurement itself. The two-port approach proposed in an earlier contribution [3] uses the acoustic impedance of the canal measured by an acoustic duct attached to its entrance to calculate H_{MT}. This method implies one-dimensional wave propagation. Hence, the pressure in cross-sectional areas perpendicular to the curved middle axis of the canal is assumed to be constant. By definition, the position and orientation of the reference areas in the one-dimensional model do not depend on frequency. The geometrical characteristics of a natural ear canal, however, cannot be simulated accurately with one-dimensional models. Due to the curvature of the canal, a more complex sound field can be expected. A comparison between three-dimensional numerical models and one-dimensional calculations yields significant deviations in the predicted pressure signals [4]. Precise calculations of the sound field in the canal can be performed in three dimensions only. In the context of the present study, a finite-element simulation of the outer ear

was implemented [5]. The pressure distribution in the ear canal was simulated and visualized by areas of equal pressure magnitude (isosurfaces), which reveal the sound field structure for different frequencies and excitation forms. Thereby, consequences for measurement concepts were derived. Additionally, the earlier contributed and the present transfer function estimation method were implemented. Thus, the gain in accuracy could be documented. Fig.1 shows parts of the model and the meshed assembly.
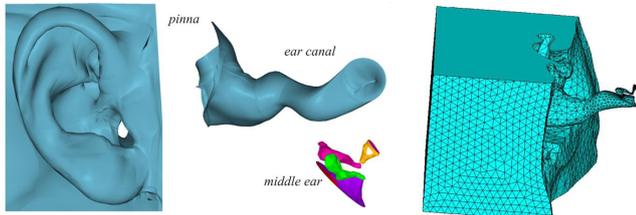
Fig.1 The finite-element model of the external ear (left: details of pinna, canal and middle ear, right: meshed assembly).

The pinna is surrounded by a rectangular box simulating an air volume. By exciting the frontal, lateral and rear boundary areas of the box (with respect to the pinna), three different near field excitation types were simulated. The eardrum is modeled as vibrating membrane with an attached middle ear model. The latter is terminated by a mass-spring-damper element simulating the inner ear impedance.

In Fig.2, isosurface plots of the simulation at 5.8 kHz (top row) and 9.1 kHz (bottom row) are shown. To the left of each subplot, the *cavum* of the pinna can be seen, to the right, the contour of the drum is visible. The magnitude minima are depicted by blue color, whereas the maxima are colored red. The left column shows the case of a laterally excited pinna, on the right, frontal wave incidence was modeled.
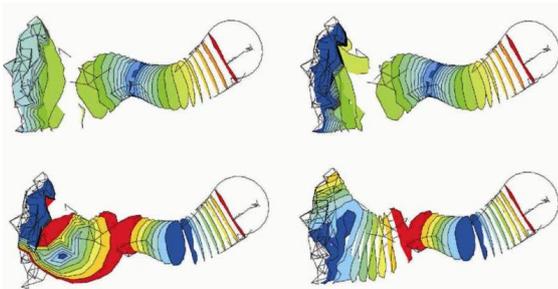
Fig.2 Pressure isosurfaces in the canal. Red: magnitude maxima, blue: pressure zeros. Top row: 5.8 kHz, bottom row: 9.1 kHz, left/right: lateral/frontal incidence.

Due to the curvature of the canal, the isosurfaces form non-planar structures, which depend on both the direction of the incident waves and on frequency. The influence of the sound source decays along the transition region between pinna and ear canal. A particular region of the canal field is independent from the source. The constant pressure distribution represents the fundamental sound field of the ear canal (the eardrum pressure itself depends on the source, of course; however, the *structure* of the isosurfaces does not). Although it is independent from the source, an essential influence of frequency can be observed in the fundamental sound field, in particular in the canal bendings. As the orientation of the isosurfaces varies over frequency, no plane reference area for the definition of an entrance

impedance can be found. Additionally, no frequency-independent middle axis exists. It can be expected, that these effects have influence on measurements that imply a two port model. Simulations of impedance measurements with acoustic ducts attached to the canal confirm the assumption. Fig.3 shows the modeled cases and the results. In each model, the ear canal can be seen on the right side. On the left, the air volumes of different tubes are visible. The tubes are excited at the left end. The entrance impedance is calculated by transforming pressure and flow signals from a location within the tube to the interface area between tube and canal.
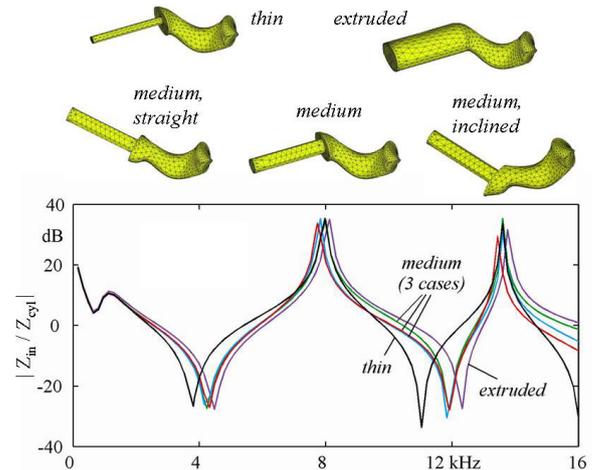
Fig.3 Top: models of impedance measurements with tubes attached to the ear canal, bottom: simulation results with reference to the input impedance of a cylindrical tube with the same entrance diameter as the model ear canal.

Fig.3, bottom, depicts the simulations results. The position of the impedance minima varies with the cross-sectional area and the inclination angle of the acoustic duct. For the determination of the eardrum transfer function based on the method proposed earlier [3], the accurate determination of the impedance minima is crucial. As no unique and precise estimation of the canal transfer function is possible, the eardrum sound pressure cannot be determined accurately when signals are related to cross-sectional areas of the canal. The pressure transfer function between *points* in the fundamental sound field, however, does not depend on the source. Point transfer functions are not subject to the variations in the isosurfaces structure, as for every given frequency unique point pressures and transfer functions exist. Consequently, an improved estimation method must implement probe microphone measurements at positions in the fundamental field.

2.2 Estimation of the ear canal transfer function

In the hearing frequency range, the eardrum can be considered as rigid boundary, except for the middle ear resonance. As the volume flow q_T into the eardrum is negligible, the point transfer function $H_{MT} = p_T / p_M$ is essentially determined by the chain parameter k_{11}:

$$p_M = k_{11} p_T + k_{12} q_T \cong k_{11} p_T \qquad (2)$$

Rather than by an inaccurate determination of the ear canal geometry, the acquisition of H_{MT} is carried out by directly estimating k_{11}. This approximation is achieved by an

equivalent system featuring the same chain parameters as the residual canal. Due to the rigid drum, the microphone pressure p_M shows distinct minima that depend on frequency and distance to the point T. The equivalent system is represented by duct model with an initially rigid termination. The two least minimal frequencies of the model impedance are adapted to the minimal frequencies occurring in the microphone pressure. The resulting chain matrix estimate is extremely accurate for all frequencies below the second minimum. The numerical fitting is achieved by adapting the length and the ratio of the termination and entrance radii in the equivalent duct model. Fig.4 (top) shows the definition of the parameters (duct length L, termination radius r_2, entrance radius r_1). The entrance impedance of the duct can be varied between a cylindrical (Fig.4, bottom left) and a conical case (Fig.4, bottom right). It is important to underline, that no geometrical approximation of the residual ear canal is achieved. Rather, the chain parameters of an arbitrarily chosen physical model are adapted to those of the fundamental field.
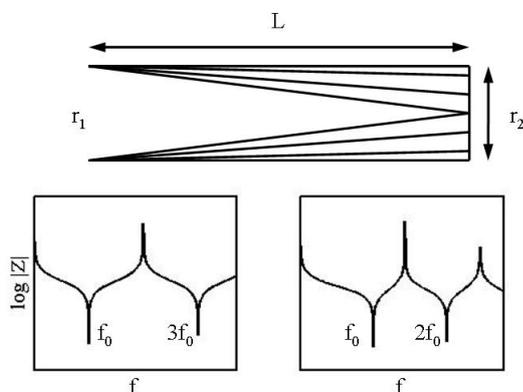
Fig.4 Top: The entrance impedance of the duct model is adapted to fit the minima of the probe sound pressure by variation of the parameters r_2/r_1 and L. Bottom: entrance impedances of cylindrical (left) and conical (right) ducts.

Assuming rigid boundaries, the transfer function of the model becomes

$$H(\beta L) = \cfrac{1}{\dfrac{r_2}{r_1}\cos(\beta L) - \left(\dfrac{r_2}{r_1} - 1\right)\dfrac{\sin(\beta L)}{\beta L}} \qquad (1)$$

with $\beta = \omega/c$, c speed of sound. For the fitting process, the second minimum has to be located within the measurement frequency range. If only one minimum can be found, a basic transformation can be achieved using $H(\beta L) = 1/\cos(\beta L)$ with L calculated from the first minimum interpreted as a quarter-wavelength resonance. Again, the parameter L must not be interpreted as real length. As the first method takes two minima into account, it will be called second-order estimation in the following, whereas the latter method is referred to as first-order estimation.

2.3 Estimation of damping

Due to losses both in the sound transmission along the canal and the eardrum vibration, the peaks of the physical transfer function H_{MT} are damped significantly. The equivalent duct model has to be complemented with loss elements to reproduce the form of the peaks accurately: It

turned out that a lumped resistance at the termination of the tube models the damping mechanisms sufficiently well. The appropriate resistance value is determined by minimizing the influence of the peaks on the resulting eardrum pressure. At the peak frequencies, the loss element is adjusted to achieve a flat frequency response. The process is illustrated in Fig.5. The probe tip pressure (green line) has a distinct minimum at 1.7 kHz. Using an undamped residual transfer function, the compensation exceeds the minimum (top blue line). As the termination resistance is reduced, the compensation overshoot drops (remaining blue lines above the red line). At a particular value of damping, the minimum becomes visible again (blue lines below red line). The fitting process is finished, when a maximal flat curve occurs (red line). In practice, the resistance is adjusted manually by the investigator. Fig.6 depicts the transfer functions occurring during the estimation process. First, the transfer function between the signal generator and the probe microphone tip is determined (green curve). After the minima have been identified, an initial tip-to-drum transfer function is computed (blue curve). The damping is adjusted (black curve) to achieve an eardrum transfer function that is maximally flat at the minimal frequencies (red curve).
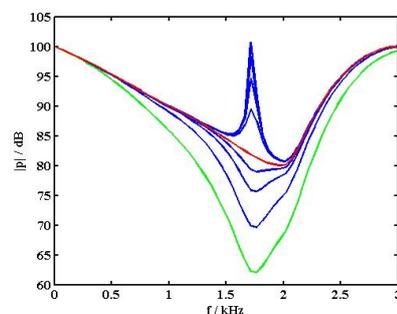
Fig.5 Eardrum pressure spectra for different termination damping adjustments, see text.
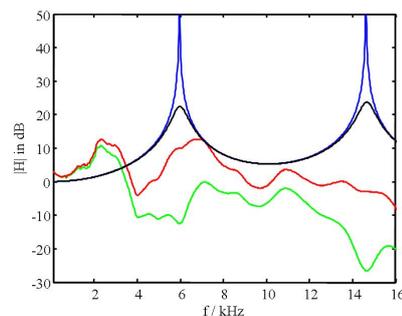
Fig.6 Example of transfer functions used for eardrum pressure estimation. Green: probe microphone pressure, blue: lossless transfer function estimation, black: damped transfer function estimation, red: eardrum sound pressure estimation.

Regarding the transducer calibration for measurements with eardrum reference, no special effort has to be undertaken, since its transfer function is canceled implicitly by the reference to the eardrum signals. The excitation spectrum, however, should be sufficiently flat to enable a robust discrimination of those minima induced by quarter-wavelength-effects and those inherent to the excitation signal. In the verification experiments, headphone excitation was used. To counteract pressure minima originating by resonances in the ear cup, foam padding was applied to the measurement headphones. It turned out to damp the notches sufficiently.

3   Verification

3.1   Finite-element simulation

A general test of the method was achieved with the finite-element model of the outer ear already mentioned in section 2.1. Again, the model was excited by three different sources. Pressure results from several positions in the canal were regarded as probe microphone pressure for the estimation algorithm. The simulation also yields the pressure at the termination point T for comparison with the estimated signals. The error between the simulated and the estimated eardrum pressure is displayed in Fig.7. The first-order estimation (blue lines) produces a maximum absolute error of 3 dB for the first two transformation lengths. At L=12.3 mm, significant deviations can be observed. Obviously, the second minimum is inadequately compensated. At L=17.3 mm, the second-order method can be applied (red lines), as the second minimum is located in the simulation frequency range. The error is comparable to the first-order estimation at L=7.2 mm. The last two cases show strong deviations, as the third and higher minima are not adequately compensated. Additionally, the different excitation modes become distinguishable. The probe position lies outside the fundamental ear canal field for these cases, as the source has a strong influence on the results. Thus, the measurements at L=20.5 mm and L=21.0 mm are not suitable for estimation.
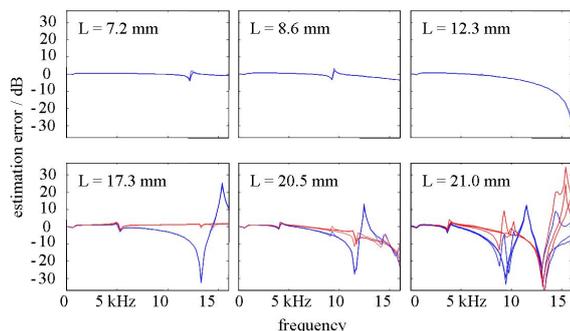
Fig.7 Errors between estimated and simulated eardrum pressures. Blue lines: first-order model, red lines: second-order model. The length parameter L was calculated from the first pressure minimum.

3.2   Measurements with an artificial ear

For a direct measurement of p_T to test the probe microphone influence, the method was applied to an artificial ear. The model consists of a silicone pinna replica (molded from a natural ear) attached to an ear canal model made from synthetic resin. At the point T, a reference microphone was installed. The eardrum is implemented as rigid termination. The model ear was excited with a damped headphone. Fig.9 displays the difference between estimated and measured eardrum sound pressure. The errors are comparable to those found in the finite-element simulation. In Fig.10, the variation of the eardrum sound pressure for different probe insertion depths is depicted. As reference, the measurement at the canal entrance was chosen. Deviations of +3/-5 dB occur. They cause no further error, because the pressure changes are cancelled by the estimation process.
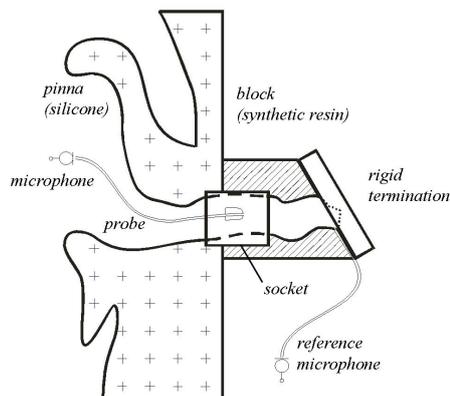
Fig.8 Artificial ear for verification measurements
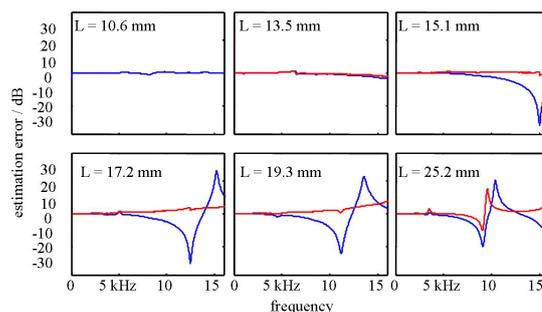
Fig.9 Errors between estimated and measured eardrum pressures. Blue lines: first-order model, red lines: second-order model. The length parameter L was calculated from the first pressure minimum.
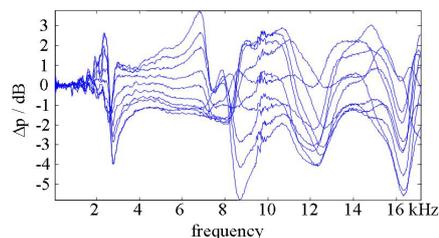
Fig.10 Variation of the eardrum sound pressure caused by different probe positions.
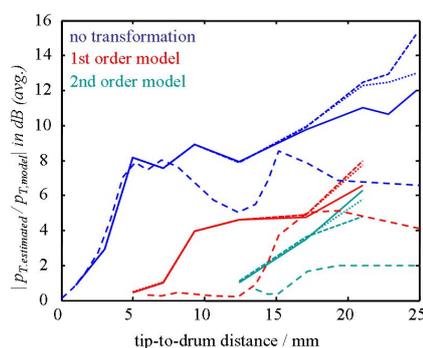
Fig.11 Average error between estimated and simulated/measured eardrum pressures. Solid/fine-dotted: finite-element model, coarse-dotted: measurement.

For comparison of different methods of estimation, the errors were averaged and displayed as function of the tip-to-drum distance determined by the first pressure minimum (see Fig.11). The finite-element results are displayed as solid and fine-dotted curves (showing the three different excitation types); the coarse-dotted lines represent the artificial ear results. If no transformation is carried out (p_M = p_T, blue curves), a distinct error occurs even if the probe

tip is positioned close to the drum. Both estimation models (red and green curves) decrease the error significantly. A second-order estimation with a tip-to-drum distance of 15 mm provides a good trade-off between accuracy and practicability. Astoundingly, the measurements yield distinctly less estimation error than the simulation.

4 Measurements of equal-loudness contours

The main issue of the estimation method is the determination of eardrum related equal-loudness contours. It can be assumed that the peaks and notches of the ear canal transfer function are not present in the measured data. Two series of preliminary measurements with varying probe insertion depth were carried out to test the influence of different tip positions on the recorded contours. In the first series, the least minimal frequency was chosen near 5500 Hz with an allowed deviation of 200 Hz (corresponding to a residual canal length of approx. 16 mm). In the other set of measurements, the probe was inserted deeper, matching a first minimal frequency of 7500 Hz with an allowed deviation of 200 Hz (corresponding to a residual canal length of approx. 12 mm).

In the experiment, three subjects between 25 and 30 years of age took part (S1, S3 male, S2 female). Contours at 30, 50 and 70 phon were measured. First, the hearing loss was examined using a commercial audiometer. No significant hearing loss was observed below 12.5 kHz. The measurement was carried out in a sound-proof cabinet. A damped, open headphone was used monaurally; the contralateral ear was occluded with an earplug. To record the equal-loudness contours, a 2AFC algorithm was used [6]. For both tip positions and each subject, four measurements were averaged. The eardrum sound pressure was estimated using a second-order model. On one subject (S1), the probe tip was brought into the close vicinity of the eardrum. The estimation was then carried out using a first-order model, yielding a distance of approx. 4 mm.
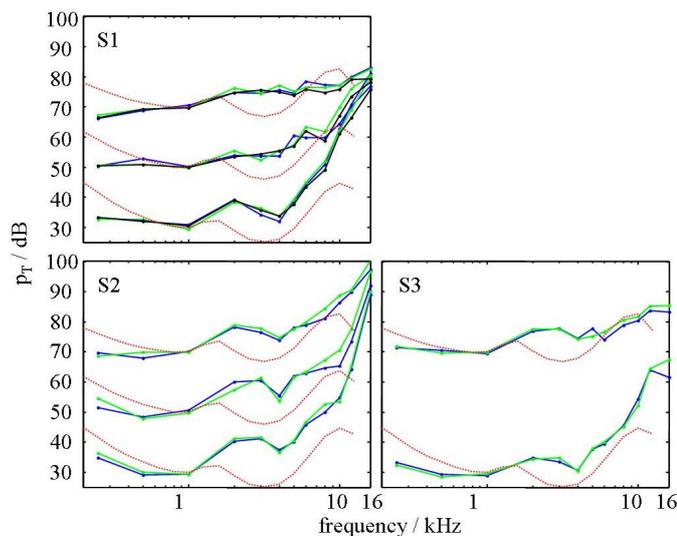
Fig.12 Equal-loudness contours for three subjects at 30, 50 (S1, S2) and 70 phon. Blue/green: data from estimations with different probe tip locations, black (S1): short distance first-order estimation, red: ISO226 curves.

The results of the experiments are shown in Fig.12, along with equal-loudness contours from the ISO226 standard for comparison. At 3-4 kHz, all eardrum related contours lack the broad minimum that is found in the ISO226 curves. As expected, the ear canal transfer function is compensated. Contrary to the assumptions, the curves are not flat around these frequencies but curved in the opposite direction. In addition, ripples can be found in some of the curves. These occurences have to be examined in future investigations with more subjects. With respect to the different probe tip positions, the equal-loudness contours show only minor deviations (max. 3 dB below 10 kHz). For S1, the same can be observed for the measurement near the drum.

5 Summary and Conclusion

Pressure measurements from positions in the canal can be transformed to the drum with the proposed method. A duct model is used to estimate the transformation characteristics of the sound field in the residual ear canal. The method is highly feasible, as only one pressure measurement for the identification of the minima is necessary. The damping of the duct model is adjusted manually to obtain a maximal flat eardrum sound pressure. This can be carried out by the investigator with a simple and robust procedure. The estimation technique was tested using a finite-element model of the outer ear and with measurements on an artificial ear. It was possible to determine the eardrum sound pressure within error limits of 2 dB. Preliminary measurements of equal-loudness contours on three subjects show, that the individual ear canal influence is minimized by the method. It can be assumed that many other psychoacoustic experiments can benefit from eardrum relation.

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