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Measurement of children's ear canal impedances using small impedance probes

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ABSTRACT

Couplers are used for the development and measurement of hearing aids. Couplers for children or babies are, however, not available due to a lack of knowledge about the correct data. A coupler imitates the impedance and the acoustic properties of a human ear canal. Recent studies have shown that the ear canal impedances of children under six years of age differ a lot from typical adult impedances. Additionally the impedances of newborn infants and children up to six years of age differ tremendously. However, the most important age group contains children younger than 2-3 years of age, since their impedances cannot be replicated by adult data any more. Nowadays the fitting of hearing aids already begins at the age of 6 months. In order to obtain correct input data, in-situ measurements are paramount. There are various possibilities to measure the input impedance on real ears, but in all cases the impedance probe must be coupled to the child's ear. Therefore, the dimensions of the probe are limited due to the small ear canal entrances of the children. When using impedance probes with a small diameter, the measurement results will be affected by acoustic losses in the small tube due to temperature, viscosity and density. The measurement is also affected by the coupling of the small tube to the ear and the resulting cross-sectional jump and the position of the loudspeaker and microphone. By using Finite-Element-Simulation the acoustic losses can be simulated as well and the simulation shows the critical areas of the measurement system. This paper deals with these problems and some approaches for measurements using very small impedance probes.

INTRODUCTION

Couplers are used for measurements and development of hearing aids. Nowadays standardized couplers are used for adults. They do not, however, replicate the ear canal of children appropriately. Fitting hearing aids for infants is thus very complicated as using adult couplers can lead to mismatches of up to 50dB. When fitting and developing hearing aids for children it is therefore necessary to carry out auxiliary measurements (for instance RECD measurements).

Studies have shown that ear canal impedances of children change over the first six years and that they differ tremendously from adult impedances. The most important age group is, however, children under the age of 2-3. The ear canal impedances of this age group differ extremely from standardized data. Most children are, however, fitted with hearing aids for the first time when they are six months old.

When it comes to developing and fitting hearing aids for children it would be great to have appropriate couplers available. Reliable measurement and simulation data is needed as they provide the basis for the development of a new coupler.

MEASUREMENT PROCEDURE

The measurement procedure to measure the impedances of the ear-canals is based on the method of the calibrated source. This method has already been used by many scientists and has been introduced related to ear canal impedance measurements by Lodwig and Hudde [1].

This method was applied to children for the first time in a study presented in 2007 [2]. The dimensions of the probe are dependent on the age of the children who should be measured, because the outer diameter needs to fit to the dimension of the ear canal entrance. In this first study, the inner diameter measured 3.5 mm and the outer diameter was 5 mm. Using this impedance probe, it was possible to measure the ear canal impedances of children aged 2 ½ years and above.

The calibration is done using three terminating impedances (cylindrical tubes of different length – material is rigid). Using a cross-fade algorithm the source parameters of the probe can be determined for a frequency range from 100 – 8000 Hz.

Since the microphone position is mounted on the side of the probe tube, at first, the impedance is calculated at this position. The required ear canal impedance, however, is at the entrance of the ear canal, according to an ear simulator or coupler. Thus, the calculated result needs to be transformed to the front of the impedance probe using a transmission line equation. This transformation is carried out without consideration of losses in [2].

Figure 1: Different impedance probes, probe tube with an inner ø = 2.5 mm mounted; probe tube with an inner ø = 3.5 mm (middle), inner ø = 0.8 mm (right)

Comparing the loss-free calculated transformation with the analytical solution, a well-defined test volume yields deviations, which correlate with the inner diameter of the probe.

The test volume is a compact aluminum cylinder with an inner diameter of 8 mm. The cylinder is 35 mm long. After mounting the impedance probe the cylinder is still 25 mm long. This arrangement is similar to the real position on human ear. The length of 25 mm corresponds to a not yet full-grown ear canal. Placing the probe on the test volume causes a cross-sectional jump which is in accordance with the real ear situation with the probe mounted and connected to the ear canal.

This situation can be modeled with a corresponding transmission line model and the target impedance of only the rigid test cylinder can be calculated exactly analytical.

If the transformation from the microphone position to the front of the probe is carried out without losses, the deviation from the analytical target impedance can be clearly seen at the position of the first resonance and also in the quality factor.

ACOUSTIC LOSSES

Acoustic losses due to heat conductivity, viscosity, density and temperature have a large impact on the measurement with the small probe tube. Especially for smaller dimensions of the probe those effects are clearly visible. The result of the transformation without losses is compared to the analytical target function in Figure 2 (red and green curve). This probe has an inner diameter of 2.5 mm and the deviation from the target function at the first resonance is clearly visible.

In order to study the effect of heat conductivity, viscosity, density and temperature the setup of the impedance probe is modeled using a transmission-line model.

The losses due to viscosity, density and speed of sound can be modeled temperature-dependent according to [3]. It turned out that especially the correct speed of sound (calculated temperature-dependent) has a big influence on the transformation from the microphone position to the probe tip. The correct speed of sound in a probe which is coupled to a human ear canal is, however, very difficult to determine in reality. This can be put down to the large temperature gradient (at probe tip coupled to the ear to the microphone position).

Modeling losses which influence the wave propagation in small tubes is done according to [4], [5] and [6]. These effects do not only take the losses due to the temperature into account, but also the effects in small tubes (those occur usually in < 3mm in diameter).

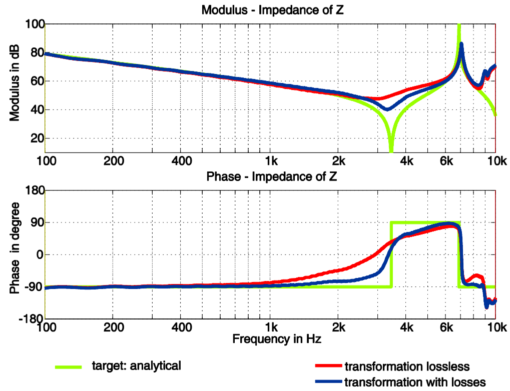

Figure 2: Impedance of the test volume, measured with a probe with an inner diameter of 2.5mm; transformation without losses (red), transformation with losses (blue).

Figure 3 shows the calculated impedances by the transmission line model at the microphone position (red line) and the transformed solution (blue line) to the probe tip for different tubes with different dimensions of the inner diameter (diameter = 1-7 mm). This shows exactly the same behavior as in the measurement. The smaller the probe tube is, the less accurate or lossy is the transformation.

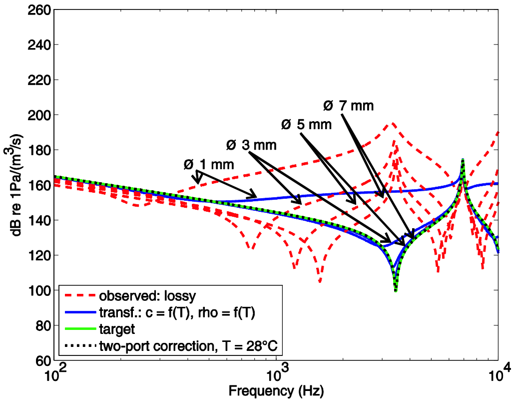

Figure 3: Impedances calculated (at the microphone position) and transformed impedances (at the tip of the probe) according to the transmission line model for different probe diameters.

If the propagation constant and characteristic impedance, is calculated according to [4] for small tubes (<3 mm diameter) losses due to temperature and loss effects at the tube walls are taken into account in the transformation.

Figure 2 shows the results of the transformation with losses (blue). We can see that the results concur with the analytical solution. Nevertheless, the analytical solution still yields superior results, as the calculation was carried out without any losses. Measurements with probes with an inner diameter of ≥ 2.5 mm yield satisfying results.

However, coupling to the ear canal of infants (approx. 6 months old) requires a smaller probe diameter. In this case other problems and non-linearities caused by the position of the microphone might occur. Further studies will show whether these non-linearities are caused by velocity or by stall

MEASUREMENT POSITION – FINITE ELEMENT-SIMULATIONS

If the sound pressure is not measured within the probe tube, but directly at the probe tip, errors caused by the transformation and lateral measurements, could be prevented.

A finite-element-simulation, that takes losses in the small tube into account, was used to simulate measurements with a small probe tube and a bigger diameter (ear canal).

In order to study the acoustic field (and impedances) near sudden contractions we have implemented and utilized a finite element (FE) model. To model the correct behavior we included both the thermal and viscous losses. This is necessary as both the thermal and viscous boundary layers have length scales comparable to geometry features of the system.

The governing equations of the system are the small parameter linearized Navier-Stokes equations (momentum), energy equation, mass conservation equation, and the constitutive equation of state. As the studied geometry is axisymmetric so is the formulation of the equations [7]. The equations are used in their weak form and have been implemented in the general weak mode of the FE software Comsol [8].

The simulated tubing system consists of a probe tube and a coupler cavity. Basically, a small diameter tube connected to a larger diameter tube. The system is actuated with a pressure source at the end of the small tube and no-slip isothermal conditions are used on all solid walls.

The FE solution provides detailed information about acoustic pressure and temperature fluctuations, and particle velocities. This enables us to study the acoustic impedance Z, in details, locally (see Fig. 4) or as mean over, e.g., a cross section.

It becomes evident, that the measurement at the tip of the probe is prone to errors. The exact position of the probe microphone at cross-sectional jump is crucial.

To carry out a flawless measurement, it is necessary to place the probe microphone into the ear canal. Otherwise the radiation pattern at the changed cross section might distort the measurement results.

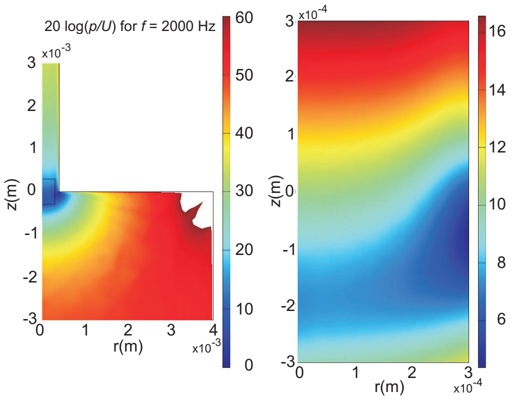

Figure 4: Impedances at the cross-sectional jump for a very small probe tube (ø = 0.8 mm auf ø = 8 mm) for 2 kHz. The figure on the right shows the area at the cross-sectional jump.

This set-up is, however, very complex and the two interconnected tubes show us the limits of this miniaturization. Furthermore, the calibration of such a probe is prone to errors. The calibration pieces have to be coupled closely to the measurement probe to achieve the required accuracy.

SUMMARY AND OUTLOOK

Measurements with impedance probes, whose dimensions are adjusted to the ears of infants and children, are influenced by losses that are, for instance, caused by thermal conduction. If these losses are taken into account, measurements with probes with an inner diameter of 2.5 mm can yield satisfactory results. If, however, probes with smaller dimensions are used, measurement faults occur, that still have to be analyzed.

A different set-up of the probe (measurement directly at the tip of the probe) was simulated by taking into account possible losses. This set-up highlighted uncertainties that depend on the exact positioning of the probe microphone.

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