Modeling individual ear canal geometries and the effect of ventilation in hearing aids

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Introduction

The geometry of individual ear canals interacts with the dimensions of a ventilation canal in determining the acoustic properties and hence the actual gain of the hearing aid. In this study, three acoustic parameters important to hearing aid design are investigated, including the hearing aid sound pressure at the ear drum, the directly through-the-vent transmitted sound pressure at the eardrum and the sound pressure at the exterior opening of the vent. For this, a comprehensive plane-wave transmission line model of the entire acoustic circuit of the hearing aid, ear and plug has been applied. In particular, the acoustic changes that the drilling of a vent entail in the performance of a hearing aid in the individual ear has been studied. The results provide an estimation of the expected variation in real ear acoustic parameters across audible frequencies in a population of hearing aid users.

Results from this modeling approach are in excellent agreement with coupler measurements in a wide frequency range. Measurements confirm the validity of the modeling approach and provide a method for assessing the vent effect, the amount of directly transmitted sound and the risk of feedback caused by a specific ventilation canal thus providing valuable information during the design phase of a hearing aid plug or shell.

Method

The simulations of the plane-wave propagation of sound from the receiver of a BTE hearing aid to the ear drum are based on transmission line theory [1,2], which is traditionally employed for cascaded-element electrical, mechanical or acoustical networks of arbitrary complexity. The elements are described by frequency dependent 2x2 transmission matrices, which are multiplied to a single transmission matrix for the entire acoustic system. This modeling approach has been validated by coupler measurements.

The two-port parameters of the receiver is adapted from Knowles circuit analog [3]. The cascade parameters of acoustical plane-wave propagation through rigid cylindrical tubes or vents with thermal and viscous damping are given by

$$\begin{bmatrix} p_{in} \\ u_{in} \end{bmatrix} = \begin{bmatrix} \cosh \Gamma l & jZ_c \sinh \Gamma l \\ jZ_c^{-1} \sinh \Gamma l & \cosh \Gamma l \end{bmatrix} \begin{bmatrix} p_{out} \\ u_{out} \end{bmatrix} \qquad (1)$$

Where p and u are the frequency dependent sound pressure and volume velocity, respectively and l is the length. $\Gamma = \sqrt{ZY}$ is the propagation operator and $Z_c = \sqrt{ZY^{-1}}$ the characteristic impedance, with Z being the series impedance and Y the shunt admittance both pr unit length [4]. In calculating the sound pressure at a distance from the vent, the vent opening is considered a point source in a flange [5].

Stinson et al [6] provided data for the geometry of 15 adult human ear canals (ECs), which is converted into simulated ECs, simplified by cascaded cylindrical thermo-viscous two-port tubes with varying diameter. The loss term originating from the viscosity along and heat conduction through the walls of the tube has been tripled to account for the damping effect of hair and compliant EC walls [7].

The ear drum (ED) properties have been assessed with the revised Shaw and Stinson coupled-piston middle ear model [8]. Due to the distributed ED, the ED model is centered at the umbo. Thus, the entire circuit is terminated by a closed volume, the Drum Coupling Region (DCR) [7].

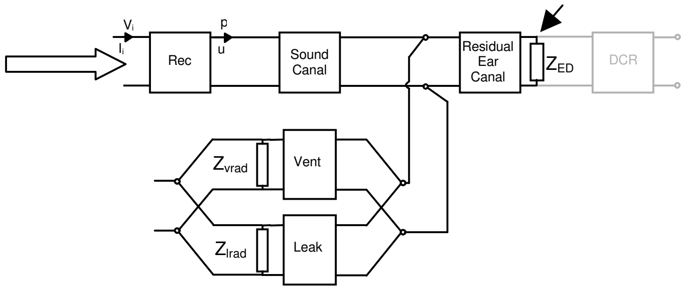

Figure 1: The transmission line model of an *in-situ* hearing aid. Each box represents a part of the acoustic network. The leakage is neglected in this paper.

Three transfer functions have been investigated:

Vent Effect: From the electrical input to the receiver to the sound pressure at the coupler microphone. The vent effect is the dB difference between open and closed vent, and accounts for the changes in the sound pressure in the coupler or ear when a ventilation canal is drilled through the ear plug. This is relevant for analyzing vent consequences.

Direct Transmission Gain: From the outside of the vent opening to the coupler microphone. The Direct Transmission Gain is the amplification of sound arising from the transmission from the surroundings directly through the vent to the coupler microphone. This is relevant for directly transmitted sound in open fittings.

Feedback Gain: From the electrical input to the receiver to the sound pressure at a distance of 2 cm from the exterior vent opening. This is relevant for feedback risk assessment.

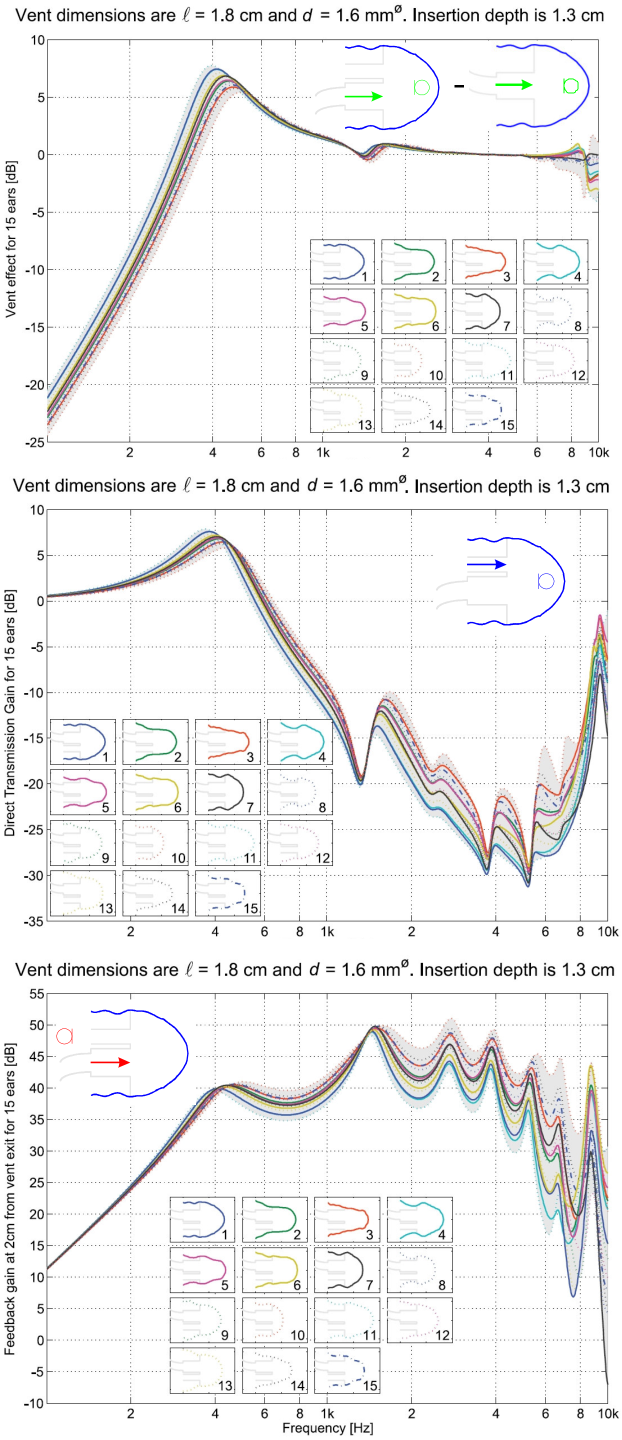

Figure 2: The spread of three acoustic transfer functions for 15 individual ear canal geometries.

Results

The ear canals vary in length between 21 mm (No 10) to 35 mm (No 11), and in mean diameter between 6 mmø and 8.8 mmø. The curves above show the vent effect, the direct transmission gain and the feedback gain calculated for these 15 ears. An infinitely tight but vented ear plug is inserted in a depth of 13 mm in all ears. The main observation is that the residual volume is the governing factor for variations in certain frequency ranges.

Vent effect: The variation in ear canal geometry gives rise to a maximum standard variation at each frequency of about 2 dB. The smallest residual volumes gives the largest numerical vent effect, due to the higher Helmholtz frequency. Small ears have a larger benefit from drilling a vent with regards to occlusion reduction.

Direct Transmission Gain: For the given vent dimensions, the plug will not attenuate sound below some 800 Hz, even though the plug is sealed. The results show that small ears allow more sound to pass through at high frequencies.

Feedback gain: Again, the effect of the varying geometry gives rise to changes above the Helmholtz frequency. Small ears thus have a larger risk of feedback.

Conclusion

This study has shown that three important transfer functions in hearing aid design can be modelled to give accurate estimations on vent effect, direct transmission and feedback risk. The model provides an extremely flexible and accurate tool for assessing these important measures in the design phase of a hearing aid. This facilitates the design of sound bore and vent geometry, insertion depth, receiver type etc. for use in any given individual ear including a possible leak between ear canal and plug. The model is applied to study the influence of the ear canal geometry on these three transfer functions. The results verifies the common notion that the residual volume of the ear canal influences the cut-off frequency of the system, and thus the frequency below which the vent effect and above which the feedback gain and direct sound is influenced by a vent.

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