Features of sound fields within and outside the ear canal

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Introduction

In the sound field between pinna and eardrum, three regions with different characteristics can be distinguished: (a) The external field is determined by the pinna geometry and the source. Surfaces of constant pressure can only be described in three-dimensional coordinates accurately. (b) In the central region of the canal, the shape of the surfaces does not depend on the source and is fairly regular. This section is often denoted as “core region” of the canal [1]. Investigations of the core region sound field are provided in a companion paper [2]. (c) Near the tympanic membrane (“eardrum coupling region”), higher order modes are excited by its shape and vibration, thus the local field does not belong to the core region.

To study the features of the sound field types in detail, three-dimensional mapping of the pressure distribution is necessary. As straightforward and efficient approach, a finite element (FE) model of a natural pinna and ear canal terminated with an elastic eardrum and middle ear components was implemented.

In this paper, characteristics of the sound field are examined by spatial visualization of surfaces with constant sound pressure (“isosurfaces”). The effect of eardrum vibrations on the field in the eardrum coupling region is investigated. It is examined, how the sound field in front of the pinna merges with the pressure distribution in the ear canal. Thus, the influence of the source on the ear canal sound field structure can be assessed.

Finite Element model

The implemented FE model is composed of a natural pinna constructed using MRI scans of a human subject, an ear canal that was designed manually and an elastic tympanic membrane which is loaded by a middle ear.

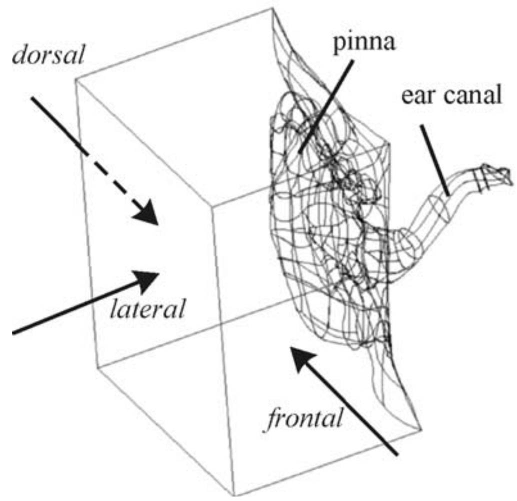

Figure 1: The "pinna box", a small air volume encompassing the pinna.

A representation of the model components is given in [2], the assembled model is displayed in Fig. 1 as wireframe plot. Details on the material and FE grid density parameters can be found in [3]. Harmonic analyses were carried out (160 Hz - 16 kHz in steps of 160 Hz) which provide complex phasors of the pressure in the simulation region.

The model pinna is encompassed by a relatively small air volume referred to as “pinna box” (cuboid structure in Fig. 1, dimensions: 80 x 70 x 50 mm). It is terminated by rectangular walls that obtain absorbing boundary conditions. The three walls indicated by arrows are used as sound sources approximating laterally impinging sound incidence and grazing sound waves from frontal and dorsal direction. Although the assignment of the specific impedance generates perfect absorbers only for perpendicular sound incidence, the pinna box turned out to provide a fairly good approximation of the free space. This has been checked in a preliminary experiment by considering the influence of box dimensions on the radiation impedance of the ear canal, which is almost unchanged, when the pinna box size is enlarged.

The sound field near the eardrum

The sound field structure at the eardrum is independent of the source. In Fig. 2, surfaces of equal sound pressure magnitude (“isosurfaces”) for different frequencies are depicted, viewing from inside through the tympanic membrane and ear canal walls. The pressure field in each panel is divided into 20 equidistant steps. Increasing gray tones indicate increasing magnitudes of complex pressure. The scale of the isosurfaces is given as level distance *D* between the pressure maximum and minimum. The point **T** in the tympanomeatal corner denotes the innermost location of the ear canal. At 640 Hz, 8 and 12 kHz, the isosurfaces are oriented perpendicular to the canal walls and to the eardrum surface. Sound waves are guided towards the point **T**, which represents the termination point of the canal. As the rim of the eardrum is approximately rigid, the sound pressure is maximal at the point **T**. At these frequencies, the eardrum behaves fairly stiff. The missing effect of eardrum vibrations at 12 kHz is immediately proven by comparison with the sound field arising for an eardrum which is made perfectly rigid (Fig. 3, right panel). The field structure is nearly identical to the elastic eardrum case (Fig. 2). The arrow at 12 kHz shows the quarter wave length minimum which appears on an isosurface. At 800 Hz, 960 Hz and 4 kHz, the middle ear and eardrum resonance alter the local sound field considerably: due to the eardrum vibrations, the maximum is shifted away from the termination point (the arrows in the panels for 800 Hz and 960 Hz indicate local pressure minima). The sound field is composed of the pressure distribution that would arise at a perfectly rigid eardrum (Fig. 3, left panel) and the near field excited by the drum vibration.

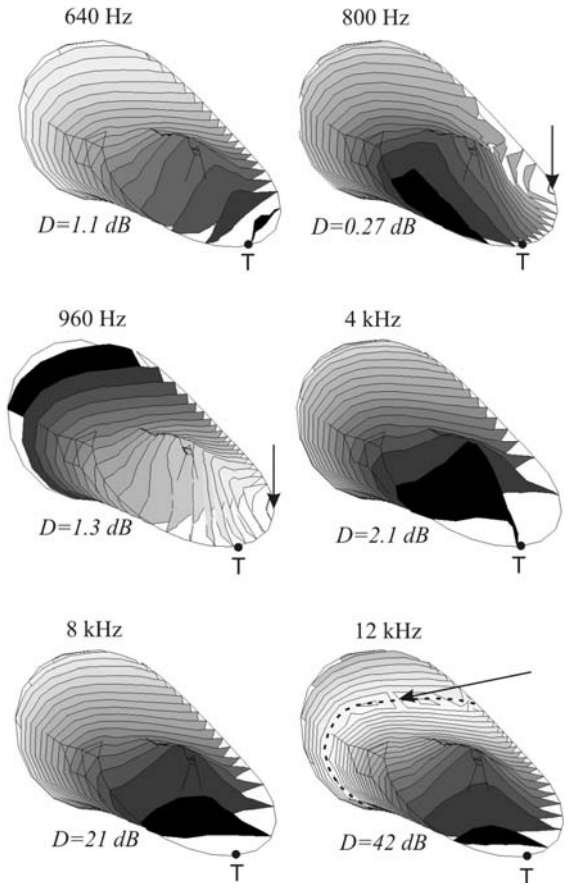

Figure 2: Surfaces of equal pressure magnitude (isosurfaces) in the eardrum coupling region at different frequencies.

The resulting sound fields cannot be modeled exactly using one-dimensional approaches. However, the wave length of sound is large in comparison to the ear canal dimensions at the middle ear resonance. In the respective frequency range, the region close to the tympanic membrane can be considered as lumped element with constant pressure. In summary, the eardrum vibrations only have noticeable impact on the sound field in the frequency range up to 3-4 kHz, for higher frequencies, sound waves are guided to the point **T** as if the drum was perfectly rigid.

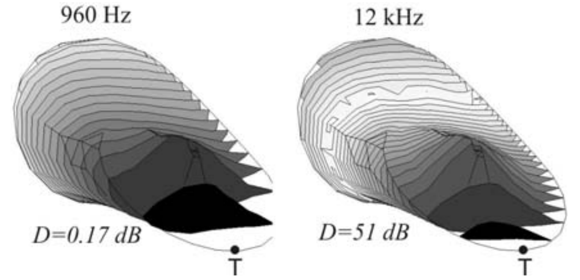

Figure 3: Isosurfaces near the eardrum at 960 Hz and 12 kHz for the case of a rigid eardrum.

Coupling of external fields to the ear canal

To get an impression of the field coupling, isosurfaces of the pressure magnitude in the pinna box and the ear canal are plotted for selected frequencies. Fig. 4 depicts the sound fields for frontal, lateral, and dorsal sound incidence as produced by the pinna box at a low frequency (320 Hz).

In the upper row, isosurfaces in the pinna box are visualized. Obviously, the vibrating pinna box walls can actually generate the desired excitation at low frequencies (as expected, the isosurface shape becomes more complicated at higher frequencies). The row below shows the pressure magnitude distribution in horizontal sections running through the pinna box and the center of the ear canal entrance. The position of this slice can be assessed by the traces of the pinna and the ear canal walls. Here the transition of the external sound field into the ear canal can be pursued.

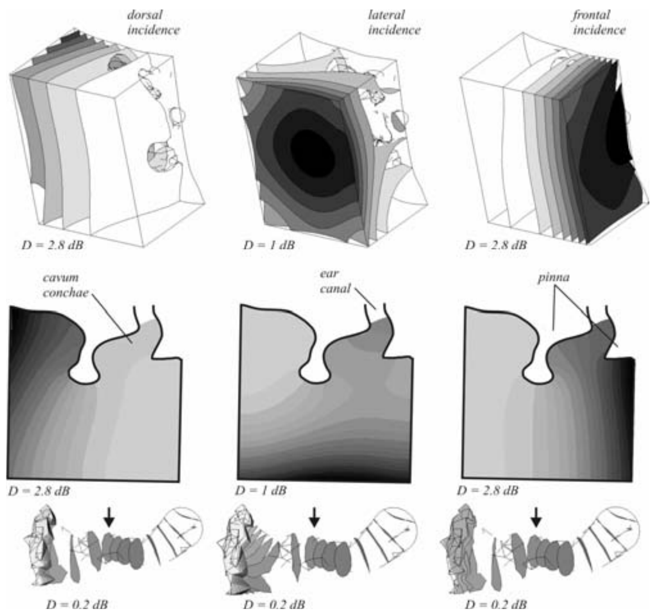

Figure 4: Sound fields in the pinna box and the ear canal for 320 Hz. Increasing darkness of gray tones indicates increasing pressure magnitude.

The bottom row shows the isosurfaces inside the ear canal which visualize variations due to the different sound sources. As expected the sound field close to the eardrum turns out to be independent of the source. The isosurfaces for lateral sound incidence are noticeably different at the position where the "entrance" could be assumed, whereas the ear canal sound fields for dorsal and frontal incidence look identical up to the beginning of the concha.

The arrows in this and the following figures point to the first surface which seems to be identical for all the three sources. Hence, the surface can be considered as entrance of the core region. This position is surprisingly far inside the ear canal. Nevertheless, at 320 Hz the absolute pressure differences are extremely small.

The ear canal sound field at 4480 Hz becomes almost independent of the source (Fig. 5). Although the sound field structure in the pinna box varies considerably, similar isosurface shapes occur at the ear canal entrance.

At 9120 Hz (Fig. 6), the sound fields for frontal and dorsal incidence are still similar, however, the sound field excited by the lateral source shows irregular structures. The arrows indicating the entrance of the core region are shifted towards the drum.

An examination of the velocity field (Fig. 7) shows as well, that the entrance of the core region depends on frequency. At

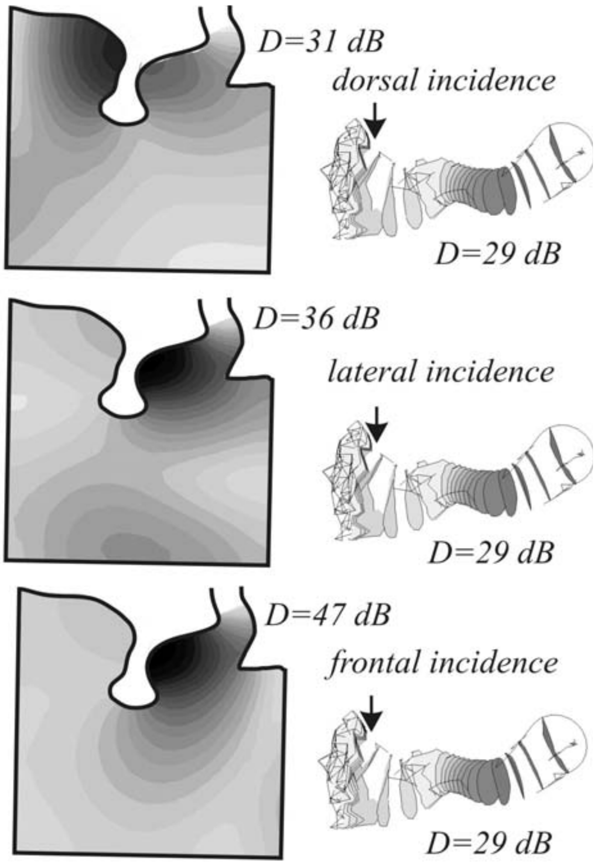

Figure 5: Sound field inside and outside the ear canal for dorsal, lateral and frontal sound incidence at 4480 Hz.

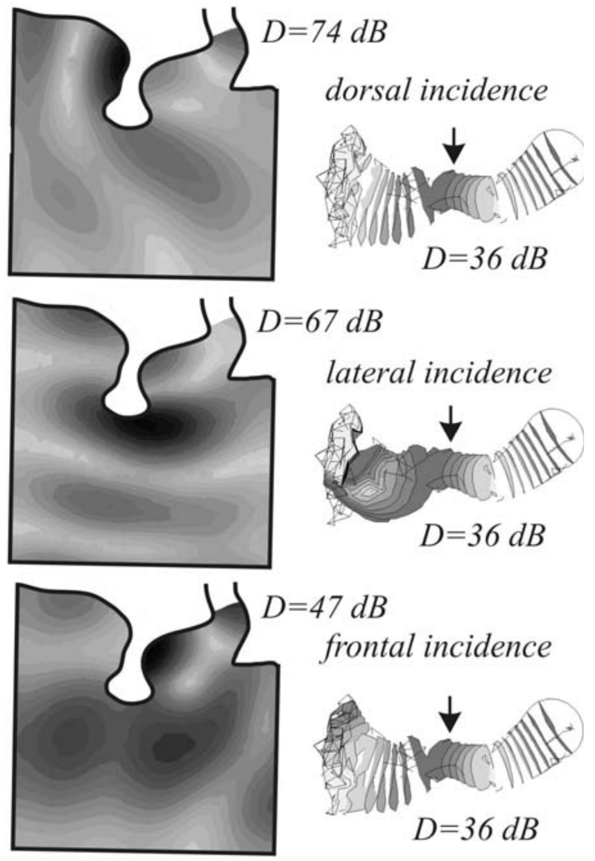

Figure 6: Sound field inside and outside the ear canal for dorsal, lateral and frontal sound incidence at 9120 Hz.

4480 Hz (top panel), a pressure minimum is present at the canal entrance. Consequently, the velocity is maximal. The velocity directions at 4480 Hz are almost identical for the three sources and constant with time. The large velocity causes a strong field interaction between the canal and the external field. Due to this effect, even the field in the inner part of the concha is independent from the source. At 9120 Hz (other panels) the direction of sound incidence significantly influences the orientation of the velocity vectors in the concha. In addition, it varies during a cycle of the oscillation (time instants t_1 to t_4). At this frequency, a velocity minimum is present at the entrance. The high ear canal termination impedance is transformed to the entrance. Thus, the pressure is not subject to any boundary condition. Due to the small velocity, the ear canal sound field is only weakly coupled to the external pressure.

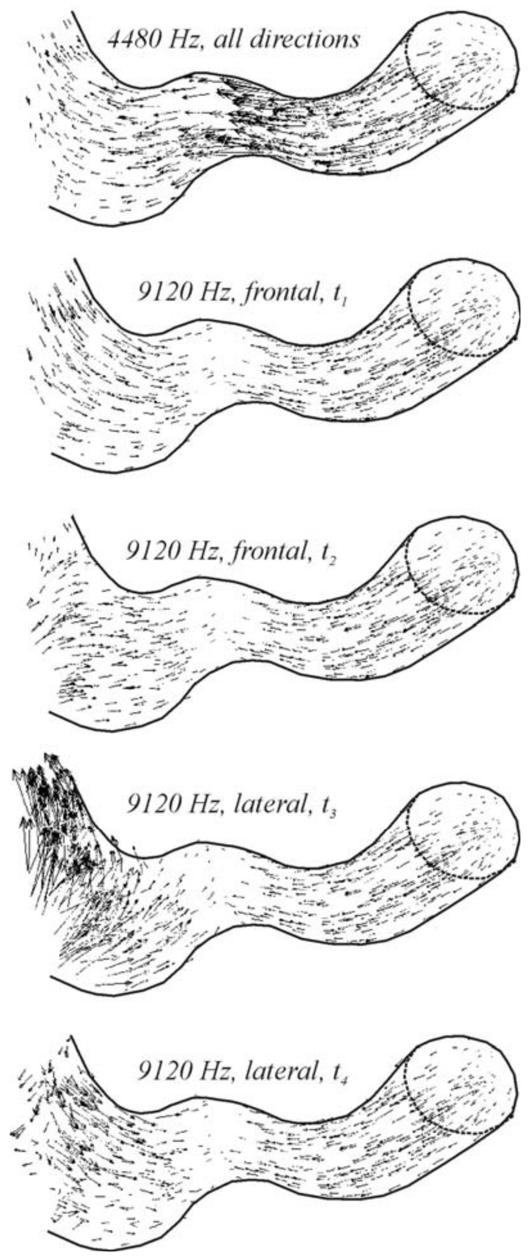

Figure 7: Velocities in the transition region between concha and ear canal at 4480 Hz and 9120 Hz.

This is also expressed by the velocity field (Fig. 7, four bottom panels). The orientation of the vectors in the concha varies during one cycle of oscillation. In the ear canal, the vector orientations are almost constant (shown for arbitrary instants t_1-t_4). With increasing frequency the distances between pressure maxima and minima become shorter. Therefore both a maximum and a minimum arise near the entrance. Discrimination of strong and weak coupling at the ear canal entrance becomes increasingly ambiguous. As a result such strong coupling as observed at 4480 Hz is not found again at frequencies beyond 10 kHz. The complexity of sound fields generally grows with increasing frequency. An example is given at 14240 Hz (Fig. 8). Here the beginning of the core region is similar to that for 9120 Hz. Generally this position does not change too much at higher frequencies.

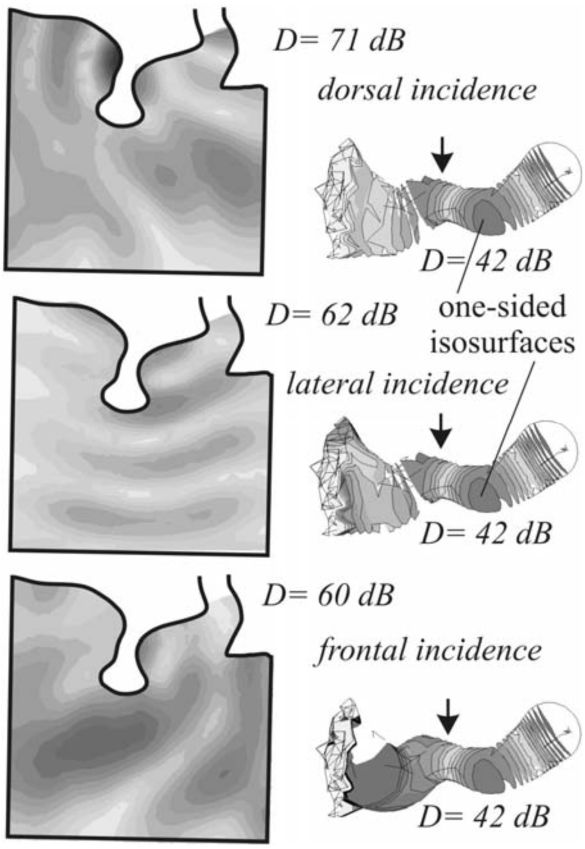

Figure 8: Sound fields inside and outside the ear canal for dorsal, lateral and frontal sound incidence at 14240 Hz.

Conclusion

The sound field in ear canals and its continuation to the concha and a volume enclosing the pinna has been investigated for sound incidence from different directions. As also found by others, the sound field can be subdivided into three parts, the eardrum coupling region near the tympanic membrane, the external part in front of an "entrance", and the core region in between.

At the end of the ear canal the vibrations of the eardrum disturb the simplicity of the fundamental sound field. At frequencies sufficiently above the resonances of the middle ear, i. e. beyond about 4 kHz, the eardrum appears to guide the sound waves like the ear canal walls because it behaves fairly stiff compared to the adjacent air. This is best seen comparing the sound fields obtained for real and rigid tympanic membranes. In the frequency range between 600 Hz and 4 kHz the eardrum noticeably radiates sound, which disturbs the simple field structure to some extent. However, the corresponding pressure variation in the eardrum coupling region remains fairly small because the wave lengths are large compared to the length of the section. These findings support circuit models replacing the true middle ear load by a lumped-element acoustic load impedance [4].

The structure of external sound fields outside the ear canal is mainly formed by the sound source and the pinna. Therefore, it has distinctly three-dimensional character. In contrast, the sound field structure in the core region, expressed by isosurfaces, is independent of the sound source and behaves essentially unidimensionally. The first surface that is independent of sources, within a certain tolerance, specifies the entrance, the beginning of the core region. Its position is mainly influenced by the location of pressure extrema near the entrance. In a pressure minimum the corresponding large velocity strongly couples the sound fields in the ear canal and the concha. In this case, the influence of the sound source becomes comparably weak, which means that the core region extends outwards up to the concha. Vice versa, a pressure maximum at the entrance decouples the outer and inner sound field, which shifts the entrance to more posterior locations into the ear canal. Using broadband excitation, the beginning of the core region is determined by the most unfavorable frequency. This yields a point immediately behind the first bend of a typical ear canal. The estimation of the entrance position according to isosurfaces is very strict. Using weaker criteria, e. g., the source independence of pressure transfer functions between a point at the entrance and a point in the rear section of the ear canal, an entrance location in front of the first bend is found. Thus, a bit surprisingly, the weak coupling allows the sound sources to influence the fields up to more posterior positions in the ear canal. Vice versa, the strong coupling established by large velocities in the transition region leads to a regular continuation of the ear canal sound field outwards to the concha and therefore to the weak influence of sound sources.

References

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