Effect of the middle ear cavity on the response of the human auditory system

Antonio Garcia-Gonzalez and Antonio Gonzalez-Herrera

*Corresponding author's address: Civil, Material and Manufacturing Engineering, University of Malaga, C/ Doctor Ortiz, s/n, MALAGA, 29071, MALAGA, Spain, AGH@UMA.ES

The effect of the acoustic cavities on the response of the auditory system has been usually focused on the influence of the external ear canal (EEC). The presence of the middle ear cavity (MEC) has been ignored. Experimental difficulties to obtain information inside this cavity without altering the whole system make difficult its study. In order to explore the influence of this cavity a numerical study is made. This is made by means of a complete Finite Element (FE) model including the Tympanic Membrane, Ossicular Chain and acoustic cavities. Different FE models are used to analyze the influence of each component. By means of different calculations removing these components from the model, their relative effects can be distinguished. At low frequencies (below 2 kHz) the influence of the MEC is negligible. Piston-like motion is dominant. Nevertheless, at higher frequencies a new resonant peak appears at a frequency of 4 kHz. This is due to the presence of the MEC. It combine with the pressure gain due to the ear canal (at a frequency of 3 kHz) increasing the response of the system in terms of Umbo velocity. This effect is observed in different published experimental results.
INTRODUCTION

The mechanics of the outer and middle ear have been the objective of much research and many publications. Some of these works use comparative methodology to deduce the function of each ear subsystem or the impact of pathological dysfunction on some subsystems (Koike et al. 2002, Gan et al. 2006, Gan et al. 2009, Lee et al. 2010, Ravicz et al. 2008, Stepp and Voss 2005, Tuck-Lee 2008, Voss et al. 2000, b, Voss et al. 2001 a, b, Voss et al. 2007). In this comparative methodology, experimental measures or numerical simulations of healthy and complete systems are made first and compared to experiment or simulated sick or purposely altered systems. Secondly, the results are post-processed and drawn together to facilitate the comparison and the function on each subsystem can be deduced. Otherwise, there are still some controversies, at present it is not clear how Middle Ear Cavity (MEC) coupled to Tympanic Membrane (TM) and External Ear Canal (EEC) affects Tympanic Membrane motion and transfer functions at high frequencies range. Therefore the main objective of this paper is to find evidences of Middle Ear Cavity role in Tympanic Membrane transfer function.

This paper is based on outer and middle ear numerical simulations developed by means of Finite Element Method (FEM). There are previous FEM works on MEC influence on TM displacement and on Pressure Gain produced by the External Ear Canal (Koike et al. 2002). A recent FEM paper (Lee et al. 2010) analyzes the effect of Mastoid Cavity in EEC pressures and Umbo Displacement. The results lead to pressure and displacement dependence on Mastoid Cavity and Aditum status (open or close). There is evidence that changing middle ear cavities produce changes in middle ear impedances (Stepp and Voss 2005), so it should affect the outer and middle ear transfer functions. Although, the frequency range is only up to 4000 Hz (Voss et al. 2000) the effect of an open Middle Ear Cavity as been shown. While these experimental results are not entirely comparable with those simulated in our FEM, there are evidence of the influence of the boundary conditions of the auditory system, reflecting waves and creating some resistance and/or resonances to eardrum deformation.

MODELS AND METHODS

Numerical simulations have been performed by means of the Finite Element Method (FEM) using the commercial software ANSYS 13.0. All numerical simulations consist of harmonic analysis in a frequency range from 100 to 20000 Hz. All models apply a unitary pressure value (1 Pa) at the entrance of External Auditory Canal as input signal. The model used for numerical simulations consists of External Ear Canal, Tympanic Membrane, Ossicular Chain (OC) with its ligaments and tendons, Middle Ear Cavity and a simplified Cochlea (SC). The model has been validated based on published experimental result.

Geometry of the different parts of the Human Auditory System

The different geometries of each subsystems have been obtained from various published works. It is assumed that differences in the geometric measurements of each individual's ears should not significantly affect the transfer functions (Koike et al. 2002) provided that the geometrical measurements fall within a normal range. All geometric measurements used for reconstruction of the FE model of this work are in that range (Caminos 2011).Therefore, the FE model representativeness is justified, and the possible variations of the geometric characteristics of the different parts of the auditory system do not alter the qualitative interpretation of results.

The geometry of the External Auditory Canal is based on the size and shape of an ear canal published in the literature (Stinson and Lawton 1989). The tympanic membrane is based on papers by Decraemer, Dirckx and Funnell (Decraemer et al. 1991). This surface has been extended to a volume to allow fluid coupling on both sides.

The geometry of the Ossicular Chain is based on that used by Weistenhöfer and Hudde (Weistenhöfer and Hudde 1999) to achieve a simplified geometry of the ossicles. The Tympanic Cavity geometry is obtained from published photomicrographs (Gulya and Schuknecht's 1996). Reconstruction of the 3D model was made from 16 sections obtained from the photomicrographs.

The geometry of the cochlea has not been modeled. It has been used as an equivalent system consisting of damper-mass-damper inspired in the literature (Gan et al. 2004), and provides very good results at low computational cost (Caminos 2011).
System Elements and properties used in modeling

**Fluid:** The external Ear Canal (EC) and Tympanic Cavity are modeled by emulating to the air. The element used is the Fluid 30 of ANSYS 13.0 (ANSYS Manual 2010). The tetrahedral shape is used and the maximum mesh size used is 0.5 mm. In all numerical examples the following properties of the fluid are constant: Density: 1.2 kg/m³. Speed of sound: 343 m/s. The damping effect has been modeled as an absorption coefficient of 0.007 at the contours.

**Eardrum and annular ligament** of the Eardrum: The tympanic membrane and the annular ligament Tympani have been modeled with solid element 185 of ANSYS 13.0. Hexahedral shape of the element has been used and the mesh size used is 200 μm. The element uses an improved formulation (Enhanced Strain Formulation) which eliminates the problems of “shear locking” of the elements used in thin membranes. This aspect is very critical because of the topology of the membrane with a thickness of 74 μm. The mechanical properties of the membrane are variable depending on whether the Pars is tense or flaccid. Table 1 shows the most important characteristics. The damping coefficient (β) has been established as $10^{-4}$ s for both components.

**Ossicular chain:** The Malleus, Incus, and Stapes have been modeled with the Solid45 element in its tetrahedral shape. The mesh size used is 400 μm. The same elements and mesh size have been used to model incudostapedial and incudomalleolar joints, posterior incudal ligament, and stapedial tendon. The tensor tympani tendon and posterior, anterior and superior ligaments are modeled as linear elements with the Beam4 element (six degrees of freedom at each node). The stapedial annular ligament is assumed to be an elastic band around the footplate 0.1 mm wide and 0.1 mm thick using Shell43 elements. Table 1 shows the most relevant properties of the Ossicular Chain. The damping coefficient (β) has been established as $10^{-4}$ s for all components.

**TABLE 1.** Mechanical properties used in middle ear components for FEM.  

<table>
<thead>
<tr>
<th>Component</th>
<th>Density (Kg/m³)</th>
<th>Young’s modulus (N/m²)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eardrum:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pars tensa</td>
<td>$1.2 \times 10^3$ a</td>
<td>$3.2 \times 10^7$ i</td>
<td>0.3 d</td>
</tr>
<tr>
<td>pars flaccida</td>
<td>$1.2 \times 10^3$ a</td>
<td>$1 \times 10^7$ c</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Malleus</td>
<td>$1.9 \times 10^3$ b</td>
<td>$1.41 \times 10^{10}$ e</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Incus</td>
<td>$1.9 \times 10^3$ b</td>
<td>$1.41 \times 10^{10}$ e</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Stapes</td>
<td>$1.9 \times 10^3$ b</td>
<td>$1.41 \times 10^{10}$ e</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Timpanic annulus</td>
<td>$1.2 \times 10^3$ (assumed)</td>
<td>$6 \times 10^5$ d</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Manubrium</td>
<td>$1.0 \times 10^3$ c</td>
<td>$4.7 \times 10^9$ c</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Tensor tympanic tendon</td>
<td>$2.5 \times 10^3$ c</td>
<td>$2.6 \times 10^6$ c</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Lateral mallear ligament</td>
<td>$2.5 \times 10^3$ c</td>
<td>$6.7 \times 10^4$ d</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Anterior mallear ligament</td>
<td>$2.5 \times 10^3$ c</td>
<td>$2.1 \times 10^6$ d</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Superior mallear ligament</td>
<td>$2.5 \times 10^3$ c</td>
<td>$4.9 \times 10^4$ d</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Posterior incudal ligament</td>
<td>$2.5 \times 10^3$ c</td>
<td>$6.5 \times 10^5$ h</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Stapedial tendon</td>
<td>$2.5 \times 10^3$ c</td>
<td>$5.2 \times 10^5$ c</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Stapedial annular ligament</td>
<td>$2.5 \times 10^3$ c</td>
<td>$2 \times 10^5$ f</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Incudomalleolar joint</td>
<td>$3.2 \times 10^3$ d</td>
<td>$1.41 \times 10^{10}$ d</td>
<td>0.3 d</td>
</tr>
<tr>
<td>Incudostapedial joint</td>
<td>$1.2 \times 10^3$ d</td>
<td>$6 \times 10^2$ g</td>
<td>0.3 d</td>
</tr>
</tbody>
</table>

The cochlea is modeled as an equivalent load, consisting of a block of rigid mass of 25.5 mg positioned between two groups of 5 dampers to each one. Each group added 0.1 Ns/m. They are distributed evenly on opposite sides of the mass block and connected to the center of the footplate. Solid45 elements with infinite stiffness are used for the mass block. Combin14 elements are used for dampers.

**Combinations of Finite Element Models**

Four different combinations have been simulated in order to discern the impact of each subsystem in the human auditory system. In Table 2 all combinations are resumed. The FE Full Model and the Ossicular Chain model with
its ligaments and tendons are shown in Figure 1.

Table 2. Combinations of FE Models simulated by means of FEM.

<table>
<thead>
<tr>
<th>Model</th>
<th>Name/Subsystems Modeled</th>
<th>Commentaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Cavity – No Ossicular Chain / EEC-TM</td>
<td>External Ear Canal linked to free Tympanic Membrane</td>
<td></td>
</tr>
<tr>
<td>No Ossicular Chain/ EEC-TM-MEC</td>
<td>External Ear Canal linked to free Tympanic Membrane and Middle Ear Cavity</td>
<td></td>
</tr>
<tr>
<td>No Cavity / EEC-TM-OC-SC</td>
<td>External Ear Canal linked to Tympanic Membrane linked to Ossicular Chain and Simplified Cochlea</td>
<td></td>
</tr>
<tr>
<td>Full Model/ EEC-TM-MEC-OC-SC</td>
<td>External Ear Canal linked to Tympanic Membrane linked to Ossicular Chain into a Middle Ear Cavity and Simplified Cochlea</td>
<td></td>
</tr>
</tbody>
</table>

RESULTS

The result showed in this paper is the UV/TMP ratio. UV is Umbo Velocity and TMP (Tympanic Membrane Pressure) is the External Ear Canal sound pressure at a point close to Umbo. This Transfer Function allows comparing results independently of the sound pressure imposed at the EEC entrance. Figures 2 and 3 show UV/TMP magnitude and phase. Fig.2a shows a comparison of experimental results with those obtained by the FEM (full model). The results reported by Rosowsky et al. (Rosowsky et al. 2012) were performed in live humans in contrast with cadaveric results reported by Nakajima et al. (Nakajima et al. 2005). The first resonance in FEM (full model) result is around 1000 Hz with a value of 0.6 mm/s/Pa. Experimental results show the first resonance among 700 Hz and 0.3 mm/s/Pa (Nakajima et al. 2005), and 1000 Hz and 0.2 mm/s/Pa (Rosowsky et al. 2012). The second resonance is around 4000 Hz for all results, with higher values for the experimental results. Figures 3a and 3b show the results obtained for UV/TMP magnitude and phase for four different combinations of the FEM. The red dashed line represents the response obtained with the full model. The green solid line represents the FEM for the model without the Middle Ear Cavity. The dashed, blue, dotted line describes the response of the eardrum in a model containing the ear canal, the eardrum and the tympanic cavity. The black dotted curve is for a model that only includes the ear canal and eardrum. It is clear that the second resonance is only observed when the Tympanic Cavity is modeled.
Figure 1. Left: Full Model Finite Element Model. Right: Ossicular Chain model with its ligaments and tendons.

Figure 2. Umbo Velocity relative to Tympanic Membrane Pressure (UV/TMP). a) Magnitude Comparison of full model–derived Umbo velocity vs. sound pressure in the ear canal with published data by Rosowsky et al. (2012), Nakajima et al. (2005), Goode et al. (1996) and Huber et al. (2001) b) Phase angle comparison

Figure 3 shows two main effects of the whole Ossicular Chain-Cochlea system on the transfer function: (1), the responses of UV/TMP are lower. This reduction is logical and expected, but not in agreement with all previous experimental paper (see discussion), and should be proportional to the energy transmitted from the eardrum through the ossicles to the Cochlea. And (2), the first resonance frequency of the system changes from 700 Hz to 1000 Hz when the Ossicular Chain and Cochlea are modeled. This fact is also observed in the UV/TMP phase, when Umbo Velocity and Tympanic Membrane Pressure are in phase. The system is in resonance when the eardrum absorbs
more energy from pressure waves coming through the ear canal. In Figure 2b, it is shown that in the two models without the Ossicular Chain, the velocity and pressure are in phase at a lower frequency than in models in which the Ossicular Chain is modeled. This is consistent with the idea that the coupling of the eardrum to the Ossicular Chain and Cochlea increases the stiffness and damping of the system.

Figure 3 also shows the main effect of the Middle Ear Cavity on the transfer function: When the Middle Ear Cavity is modeled; two resonance peaks around 4000 and 12000 Hz are appreciated in the transfer function. In Figure 3b, where the phase is shown, is also remarkable this fact. The green and black lines correspond to models without Middle Ear Cavity, and they do not reproduce the typical shape of a resonance.

**DISCUSSION**

As described in the Results, the main difference observed between the results in the models with and without Middle Ear Cavity is the appearance of a second resonance in the transfer functions of the eardrum. This second resonance is between 3500-5000 Hz.

There are differences in the results of Eardrum transfer functions presented in experimental papers. This is justifiable because there are differences between pilot operational methods in the preparation of the temporal bones, the measurement instruments used, and the inherent geometry of each analyzed auditory system (Aibara 2001). If we focus on the second resonance at the transfer functions in frequencies from 3000 to 6000 Hz, in some experimental results this second resonance is very noticeable in some of them it is barely noticeable, and in others is not appreciated. This may be related to the degree of opening of the middle ear cavities shown by the experimental results with measurements made with closed and open cavities (Willy 2003, Fig V7). All the experimental results shown in Figure 1 were made with closed cavities. Other experimental results have not been showed in this paper: Kringlebotn results (Kringlebotn et al. 1985, closed cavities) show the second resonance around 7000 Hz; for Chien...
results (Chien et al. 2009, Fig.9 open cavities), the recovery of the stapes response is located around 5000 Hz; In Aibara results (Aibara et al. 2001,closed cavities) the resonance is around the 5000 Hz; Nakajima(Nakajima et al. 2008 open cavities, Fig 2-5) represents the transfer function from ear canal pressures to scale vestibule pressures. The difference in the frequency of the second resonance could be due to geometrical differences and boundary conditions in the middle ear cavities, as action protocols differ in the temporal bone. Volandri (Volandri et al. 2011, Fig. 5) presents a compilation of results from displacement of the eardrum in humans showing many Tympanic displacement results. The second resonance is seen in some articles and not in others. The second resonance is clearly seen in the experimental results for which the middle ear cavities were closed. The experimental results where the second resonance did not appear were obtained with open Cavities (Gan et al. 2004). In other results where the second resonance appears, the middle ear cavities were also open (Chien et al. 2009, Nakajima et al. 2008). Therefore, there is a controversy on this fact. There are at least two considerations to be taken into account for explaining this issue: most of experimental results show the mean average of several measurements in different individuals and the second resonance frequency can be different due to geometrical and boundary conditions differences of the middle ear cavities. This fact could lead to a compensation for the resonance. Another important fact is that opening the middle ear cavity does not imply the elimination of the cavities (this FEM paper models closed cavity or nonexistence of cavity), but it implies a change in boundary conditions. The middle ear cavity remains with different conditions and most of the middle ear walls remain reflecting waves. Evidently, the resonance frequencies will change. The size of the cavity holes in the experimental results reported in the literature is not clear, therefore it is necessary to develop in the future new FE models in order to represent these experimental situations: open middle ear cavities in a similar way to experimental set up, and to perform an analysis of the hole size and position effects. It would also be very interesting to develop further experimental with variations of these conditions, there is at least one previous work focused on it (Voss et al. 2000), but only show results up to 4000 Hz.

Comparing the results obtained in this paper with other FE paper in the human auditory system, we found that in those where the middle ear cavities are not modeled, the second resonance at the Umbo or stapes transfer function is not found (Koike 2001, Lee et al. 2006). Some works do not show transfer functions, they show graphs of displacement instead (Ferris et al. 2000, Lee et al. 2010). If the input pressure is applied at External Ear Canal entrance, it is not possible to distinguish if the resonance is due to middle ear cavities (if they are modeled) or to ear canal. Koike et al. presented an analysis by means of FEM of the open middle ear cavities effect (Koike et al., 2002), a small resonance around 4000 Hz is shown in the response of Umbo when cavities are closed. When cavities are opened, the resonance disappears. In some works where cavities are modeled, the second resonance is not found (Gan et al., 2004, 2006, 2007).

CONCLUSIONS

We find evidences resulting that the Tympanic Cavities presence in the auditory system introduces a second resonance in middle ear transfer functions at frequencies higher than 3 kHz. The eardrum is undoubtedly the most influential subsystem in UV/TMP transfer functions. UV/TMP magnitudes are strongly affected by the ossicular chain and the cochlea attachment, but phase is only slightly affected.

The experimental and numerical studies should complement each other, the experimental results are used to make reference measurements and validate numerical models. Once they are validated, the numerical models should be used to perform simulations that represent situations very difficult or even impossible to experience in a laboratory in order to explain the causes of the observed phenomena.

REFERENCES

Annals of Biomedical Engineering. 32, 847-859.