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ANALYSIS OF THE MECHANO-ACOUSTIC INFLUENCE OF THE HEARING SYSTEM COMPONENT IN THE EAR CANAL PRESSURE DISTRIBUTION

GARCIA-GONZALEZ, A.

*Dpto. Ing. Civil, Materiales y Fabricación, Universidad de Málaga, University Department,
Calle Doctor Ortiz Ramos (Teatinos)
Málaga, 29071, España
tolin@uma.es
<http://<webaddress>>*

CASTRO-EGLER, C.

*Dpto. Ing. Civil, Materiales y Fabricación, Universidad de Málaga, University Department,
Calle Doctor Ortiz Ramos (Teatinos)
Málaga, 29071, España
kceglar@uma.es*

GONZALEZ-HERRERA, A.

*Dpto. Ing. Civil, Materiales y Fabricación, Universidad de Málaga, University Department,
Calle Doctor Ortiz Ramos (Teatinos)
Málaga, 29071, España
agh@uma.es*

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Conclusion: Two main conclusions have been deduced. First, the Pressure Gain distribution along the Ear Canal is strongly dependent on boundary conditions, and, in normal conditions, the Ear Canal produce a 0-20 dB pressure gain close to the Tympanic Membrane in 100-20000 Hz range. Second, Pressure Gain distribution along the Ear Canal at high frequencies (over the second resonance of the Ear Canal at 8000-9000 Hz) depends strongly on the axis position, so the middle ear transfer functions based on the Ear Canal pressure are also strongly dependent on the measuring point. Objective: The objective of this paper is to deduce the mechanical influence of Tympanic Cavity, Ossicular Chain and Tympanic Membrane connections in the Ear Canal pressure in a frequency range of 0.1 to 20 kHz when pressure source is applied in the Ear Canal entrance. Methods: Numerical simulations have been developed for seven different models by means of Finite Element Method. Based on an External Ear Canal Finite Elements model, the additional elements are coupled and removed in order to evaluate the contribution of each one. Tympanic Membrane, Ossicular Chain, Simplified Cochlea and Tympanic Cavity have been modeled and simulated in seven different combinations. Results: Pressure distribution along the External Ear Canal are obtained and represented in 100-20000 Hz range for the seven model configurations.

Keywords: Ear canal; middle ear; tympanic membrane; tympanic cavity; finite element

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analysis; resonance.

1991 Mathematics Subject Classification: 22E46, 53C35, 57S20

1. Introduction

Since recent years Finite Element modeling has become a powerful tool to understand the behavior of the human hearing system. One of his potentialities is that we can simulate the whole system and then modify it to evaluate the contribution of each separated component. This paper presents part of a broad study made with a whole FEM of the human hearing system including Tympanic Membrane, Ossicular Chain, Simplified Cochlea and Tympanic Cavity. This model has been built in order to allow us to remove each component with the aims of simulate this system in different configurations. In the study of the hearing system it is of particular interest the analysis of the influence of the mechano-acoustic phenomenon present among the acoustic cavities and the mechanical system. Its relevance in the mechanics of hearing it is not clear, especially at higher frequencies. In the present paper we will focus on the analysis of the pressure distribution inside the ear canal. The different contribution of each component of the system is evaluated. There is only a few works on bibliography dealing with this matter. Experimental work is limited by the difficulties of measuring sound pressure inside the cavities without disturbance. Regarding numerical studies, Finite Element Method (FEM) has been used in some work. The effect that eardrum holes produce in the pressure gain distribution in key points of the outer and middle ear has been studied by means of FEM¹²³. The main conclusion was an important Tympanic Cavity (TC) role in Pressure Gains when the Tympanic Membrane (TM) was perforated, in agreement with those conclusions found in this paper. Another paper based on experimental and lumped model results⁴ demonstrated that TM perforations, Tympanostomy tube, and Mastoid bowl strongly affect Pressure Gain in EC. These conclusions partially agree with those obtained in this paper. There is a recent FEM paper⁵ that analyzes the effect of Mastoid Cavity in EC pressures and Umbo Displacement (not in transfer function). The results lead to pressure and displacement dependence on Mastoid Cavity and Aditum status. This paper summarizes the main result obtained to illustrate the mechanic-acoustical influence of the Tympanic Membrane, Tympanic Cavity, and Ossicular Chain connection in the External Ear Canal Pressure.

2. Materials and Methods

Numerical simulations have been developed 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 use a unit value pressure at the entrance of External Auditory Canals an input signal. The Finite Element Model (see Fig. 1) have been previously developed and validated

⁶⁷⁸.The subsystem have been modeled were: Ear Canal (EC), Tympanic Membrane (TM), Ossicular Chain (OC), Tympanic Cavity (TC) and Simplified Cochlea (SC). Seven different combinations have been calculated (See Table 1) in order to discern the impact that each subsystem produce in the pressure gain.

3. Results

Fig. 2 show the frequency response of Pressure Gain in dB close to the Umbo for experimental test and our seven combinations. Fig. 3 show the frequency response of Pressure Gain in dB along the EC normalized to the unit pressure value at the EC entrance. It is represented the gain at the center of EC's entrance ($z=0$ m) straight to the Umbo ($z = 32e-3$ m). In Fig. 4 the Tympanic Cavity Pressure Gain is represented up to the footplate ($z = 40e-3$ m). The dB scale is relative to the input value corresponding to 1 Pa (0 dB). Fig 2a shows a comparison among Full Model (FEM) and numerical results of the frequency response of Pressure Gain close to the Umbo. There is a good correlation for first resonance frequency: FEM reports 15 dB at 3800 Hz, the lowest experimental result is 11 dB at 3200 Hz⁹, and the highest experimental result is 14 dB at 4400 Hz¹⁰. Therefore, the correlation for the second resonance is not as good as for the first. In general, FEM predicts almost 20 dB instead those 5-12 dB obtained experimentally. Fig. 3b shows a comparison of the frequency response of all combinations for $z = 0032$ (position close to Umbo); this graph facilitates the comparison of the frequency response results obtained in a key point (close to Umbo).

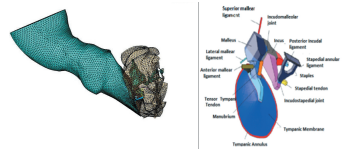


Fig. 1. Left: Full Model Finite Element Model. Right: Ossicular Chain model with its ligaments and tendons.

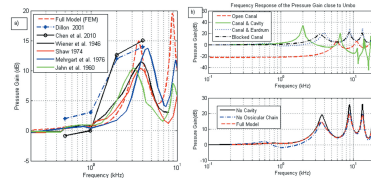


Fig. 2. a) Comparison of the frequency response between Full Model (FEM) and experimental results (position close to Umbo): Wiener et al. 1946, Shaw 1974, Mehrgardt et al. 1976 and Jahn 1960 b) Comparison of the frequency response for all combinations at $z = 0.032$ (near the Umbo).

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Fig. 3b and Fig. 4a show that first resonance is around at 2 kHz in the models that the tympanic Membrane has not been modeled. These results are also consistent with theoretical calculations of the 1st resonance frequency in a cylinder, where the first frequency value is inversely proportional to the length of a cylinder. On the other hand, the 1st resonance frequency is around 4 kHz when the Tympanic Membrane was modeled. Regarding the Ossicular Chain function, there are no significant differences in the distribution of Pressure Gain along the EC (Fig. 4b-c). In the absence of tympanic membrane, the pressure peaks in Fig. 3b and Fig. 4a coincide with other works³, which shows the experimental and numerical frequency response results of pressure in the EC and Tympanic Cavity with perforated eardrums. The first response peak is located around 2000 Hz, and the second between 6000 and 7000 Hz. The peaks in the pressure distributions in the EC are due to the new boundary conditions, where the acoustic coupling of the EC and TC prevails.

4. Discussion

The effect of the EC's position on the pressure is observed in Fig. 3 and Fig. 4. Depth is not a key parameter in the Pressure Gain distribution along the EC up to 1000 Hz (except for open EC and EC-TC configurations). Depth is a key parameter in 1000 to 4000 Hz frequency range. Pressure Gain is greater the closer we get to the eardrum. These observations are consistent with previous experimental results¹¹¹²,

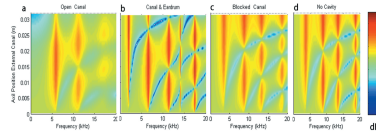


Fig. 3. Frequency response of pressure gain in dB along the axis Ear Canal, from EC's entrance ($z=0$) straight to the Umbo ($z=0.032e-3m$) in a) Open Canal b) Canal and Eardrum c)Blocked Canal and d) No Cavity.

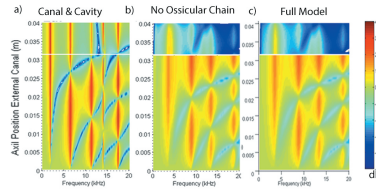


Fig. 4. Frequency response of pressure gain in dB along the axis of Ear Canal and Medium Ear Cavity, from EC's entrance ($z = 0$) through the Umbo ($z = 0.032e-3m$) until the oval Window ($z = 0.04e-3m$). a) EC connected to Tympanic Membrane and Tympanic Cavity. b)Ear Canal connected to Tympanic Membrane, Ossicular Chain and Simplified Cochlea c) Complete model.

but these experimental papers only show results up to 4000 Hz frequency. It can be deduced from our results (See Fig. 3 and Fig. 4) that the Pressure Gain distribution along the Ear Canal has a strong dependence on depth (Axial Position) above 4000 Hz. Between the first resonant frequency (around 4000 Hz) and the second resonance frequency (around 8000 Hz) there is a dip. Similar results are obtained between the second and third resonance (around 14000 Hz), but with two dips. Between the third and fourth resonance frequency (around 18000 Hz), there are three dips. The relation of pathologies (TM perforations and Mastoid bowl) with variations in the Pressure Gain distribution along the ear canal has been previously reported⁴. The results of this study reaffirm this hypothesis; it is proved that the Pressure Gain distribution along the Ear Canal is seriously affected by the absence of the eardrum or when the Ear Canal is coupled to an additional cavity. On the other hand, the results of this study do not establish a relationship between EC Pressure Gain distribution and ossicles chain or cochlea diseases. This fact can be observed in Figs. 4b-c, where Pressure Gain distribution along the EC is almost unaffected by the presence of the Ossicular Chain and Simplified Cochlea. We have not found previous papers to compare with this conclusion. Some previous papers established that pressure in the Tympanic Cavity can be considered constant to 4000 Hz²¹³. The results obtained in this paper (see Figs. 4b-c) agree with these statements.

5. Conclusions

The Pressure Gain distribution along the EC is strongly dependent on boundary conditions, and, in normal conditions, the EC produce a 0-20 dB pressure gain close to the TM in 100-20000 Hz range. It is clear the amplifier function of the EC near the eardrum compared with the inlet pressure at EC entrance. Throughout the EC there are gains and losses regions, but in all cases in which the eardrum was modeled. The positive gain in the eardrum vicinity above 1000 Hz is clear. Regarding the resonance frequencies values, the most influential subsystems are undoubtedly the EC and eardrum. The Ossicular Chain and the Cochlea are the subsystem with less impact on the pressure gain distribution along the EC, both the value of pressure gains as well as the range of frequencies that occur in them. The coupling of the tympanic cavity to the eardrum slightly affects the pressure gain distribution in the EC. It generates a small decline in gains around the eardrum, and a small variation of the frequency response. Another relevant conclusion of this study that Pressure Gain distribution along the Ear Canal at high frequencies (over the second resonance of the Ear Canal at 8000-9000 Hz) depends strongly on the axis position. It has important consequences when evaluating the middle ear transfer functions based on the Ear Canal pressure as it is strongly influenced by the experimental measuring point.

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Table 1. Combinations of finite elements models simulated by means of FEM.

Model	Name/Subsistem modeled	Commentaries
	Open canal/ EEC-Absortion Semi-Sphere	External Ear Canal linked to Absorption Semi-Sphere
	Blocked canal/ EEC-TM	External Ear Canal linked to a Blocked Tympanic Membrane
	Canal and Eardrum/ EEC-TM	External Ear Canal linked to free Tympanic Membrane
	Canal and Cavity/ EEC-MEC	External Ear Canal linked to a Middle Ear Cavity
	No Ossicular Chain/ EEC-TM-MEC	External Ear Canal linked to free Tympanic Membrane and Middle Ear Cavity
	No Cavity/ EEC-TM-OC-SC	External Ear Canal linked to Tympanic Membrane linked to Ossicular Chain and Simplified Cochlea
	No Cavity/ EEC-TM-MEC-OC-SC	External Ear Canal linked to Tympanic Membrane linked to Ossicular Chain into a Middle Ear Cavity and Simplified Cochlea

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