# NUMERICAL MODEL TO SIMULATE THE FORWARD AND REVERSE SOUND TRANSMISION MECHANISM IN HEARING

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## ABSTRACT

*The human hearing system captures acoustic waves in air that are transmitted to the cochlea where are converted in nerve signal. Meanwhile, at the cochlea, some sensory cell are active provoking sound transmission in the reverse direction. These called otoacoustic emissions are measured in the ear canal as diagnostic method. Forward and reverse transmission mechanisms are complex being a matter of research. Its study presents great difficulty, either by experimental or numerical methods.*

*A simplified experiment has been designed to evaluate both mechanisms. It consists of a system with the basic elements (air, tympanic membrane and ossicular chain).The present paper presents results corresponding to a previous numerical study. Methodology is described, it is based in previous work. Main results are shown in terms of modal analysis and sound pressure fields.*

*Comparing with the behavior of a membrane , the presence of the umbo adds stiffness and mass to the system. Results prove that the effect of the mass is more significant, increasing the number of modes present in the range of frequency of interest. Comparing forward and reverse mechanisms, the main difference is on the side of the stimuli, similar to the opposite side.*

## 1   INTRODUCTION

The human hearing system is a complex mechanical system intended to capture acoustic waves in air and transmit them to the cochlea responsible for the transduction in a nerve signal. In its basic behaviour sound is collected by the pinna (ear) and conducted through the ear canal to the tympanic membrane (TM). The TM transforms the acoustic waves in mechanic vibrations which are transmitted through the ossicular chain to the oval windows on the cochlea. There, an acoustic wave is propagated in the fluid displacing the basilar membrane where sensory cells are placed (hair cells). These cells produce the nerve signal. This is the forward transmission mechanism.

Part of these cells (outer hair cells) present motility capabilities. This active mechanism enhances the sensitivity of the transduction and produces sound inside the cochlea (otoacoustic emissions, OAEs). This wave is transmitted to the ear canal. This is the reverse transmission mechanism. OAEs can be measured at the ear canal and is the base for different diagnostic techniques.

Forward and reverse transmission mechanisms are not symmetric and both are matter of research currently. Its study, either by experimental or numerical methods [1,2,3], presents great difficulty due to the complexity of the system and the coupling of different phenomena. So a simplified experiment has been designed to evaluate both mechanisms. It consists of a system where the basic element are present (air, TM and ossicular chain) and can be controlled. In the present paper, results corresponding to a previous study based on a Finite Element model are shown.

## 2   EXPERIMENT DESCRIPTION

An scheme of the experiment is displayed on Fig 1. It is based in previous works where a membrane was subject to a sound stimuli and its response measured by different methods [4,5]. The membrane is supported by a baffle that blocks sound to the opposite side.
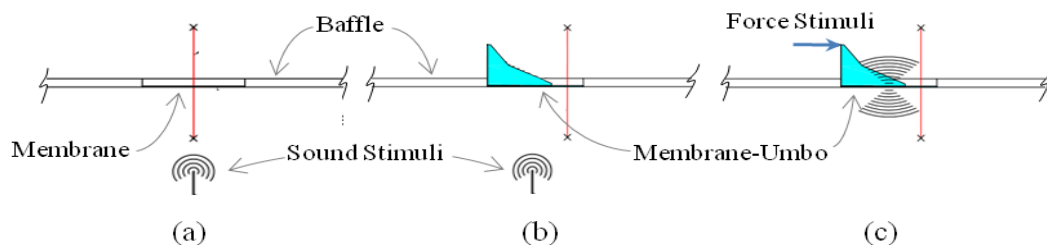


Figure 1. Experiment setup.

An additional piece is added to the membrane. It represents the part of the malleus bone in contact with the TM (umbo). This is a simplified way to represent the effect of the ossicular chain. With this system, forward and reverse mechanism can be modelled. When the system is subject to sound stimuli, displacement can be obtained at the tip of the umbo (Forward transmission, Fig 1b). Alternatively, a force or displacement can be applied at the tip and membrane motion and sound pressure can be measured (Reverse transmission, Fig 1c).

Dimensions resemble the human system. Diameter is 1 cm and thickness 100 um. The umbo extend to 2/3 of the diameter. The umbo high is 0.5 cm and the thickness 0.3 mm. Stimuli is applied at a distance of 1 cm from the membrane. The mechanical properties of the material are: density 1200 Kg/m$^3$, Poisson´s ratio 0.35 and Young´s modulus 2 GPa.

## 3   NUMERICAL METHODOLOGY

A brief description of the methodology will be made. It follows previous works and details can be consulted in references [4,5]. The FE model is shown in Fig 2 with a detail of the membrane-

umbo model in Fig 2b. It is composed by three parts, a rigid solid (baffle and sound source), an elastic body (membrane-umbo system) and the fluid surrounding. The solid domain is considered as a rigid body and is represented by the correspondent motion constraint (as rigid surfaces).
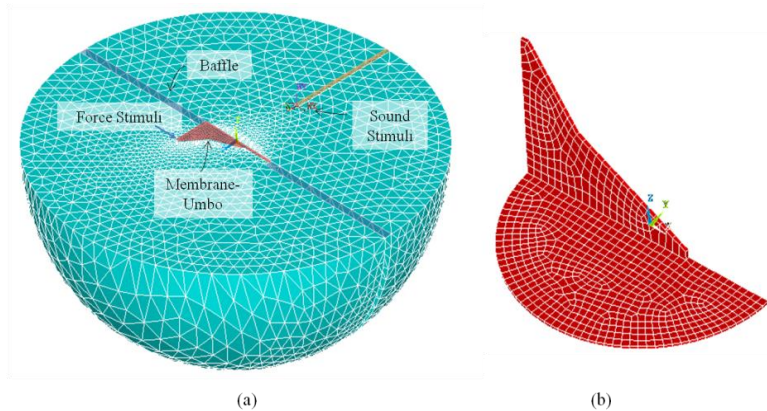


Figure 2. Finite Element Model.

The others two domains conform the numerical model, the elastic domain corresponding to the membrane-umbo system and the fluid domain represents the surrounding air. A coupled fluid-structure interaction problem is implemented in their contact areas. The fluid is bounded by an sphere to represent open field condition. Its surface is meshed with an element which represents a fluid domain that extends to infinity. The speaker is modeled as a rigid cylinder with dimensions similar to the real one. Symmetry is applied and only half problem is modeled. The fluid is meshed with acoustic elements and the membrane with eight nodes solid element.

The influence of other modeling parameter (mesh size, element formulation, sphere size...) has been analyzed and carefully selected. Especial care is paid to the mesh size, selected according to previous studies [5]. An harmonic analysis has been done for a range of frequencies from 0 to 20 kHz. Additional modal analysis has been done to obtain modal shapes and frequencies**.**

## 4   MODAL ANALYSIS

Modal analysis provides a first sight on the response of the system. Mode shapes are displayed on Fig 3 and frequencies in Table 1. The membrane follows the classic pattern. Membrane-umbo modes show more irregularity. Unless the first frequency is similar (aprox 2.5 kHz), the other modes tend to be lower with more modes present in the range of frequency of study. This means that the stiffness increase is cancelled by the mass added.
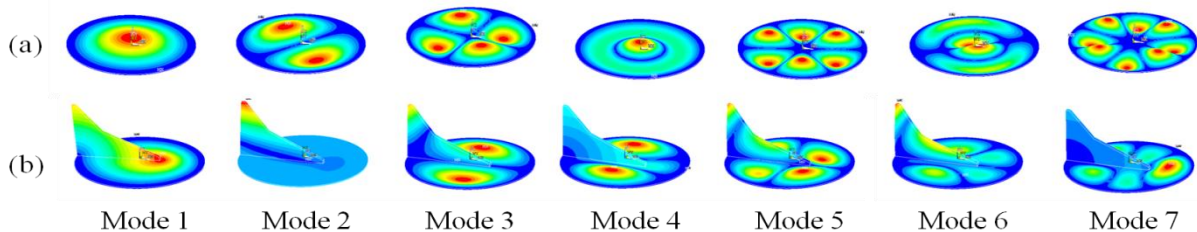


Figure 3. Modal shapes. Membrane (a) and Membrane-Umbo (b)

| mode | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Membrane | 2.56 | 5.33 | 8.78 | 10.1 | 12.8 | 15.4 | 17.5 | 21.5 | 22.7 | 28.2 |
| Membrane-Umbo | 2.4 | 2.9 | 6.3 | 8.1 | 10 | 10.7 | 13.1 | 14.4 | 16.7 | 17.2 |

Table 1. Modal Frequencies (kHz).

## 5   RESULTS

Many variables can be obtained (velocity, sound pressure). Sound pressure fields are one of the most relevant. On Fig. 4, sound pressure is plotted along lines normal to the membrane (shown in Fig 1) with a double spatial and frequency domain. Spatial z axis corresponds to the distance to the membrane, placed at z=0, negative values are closer to the stimuli. The different behaviour are easily visualized. Comparing (a) and (b), the presence of the umbo is manifest with a higher complexity in the response due to the higher number of modes present in the range of frequency of interest. Comparing forward (b) and reverse (c) behaviour, it can be observed how the response is symmetric in the reverse case, and very similar to that obtained in (b) for the sound transmitted to the opposite side of the stimuli.
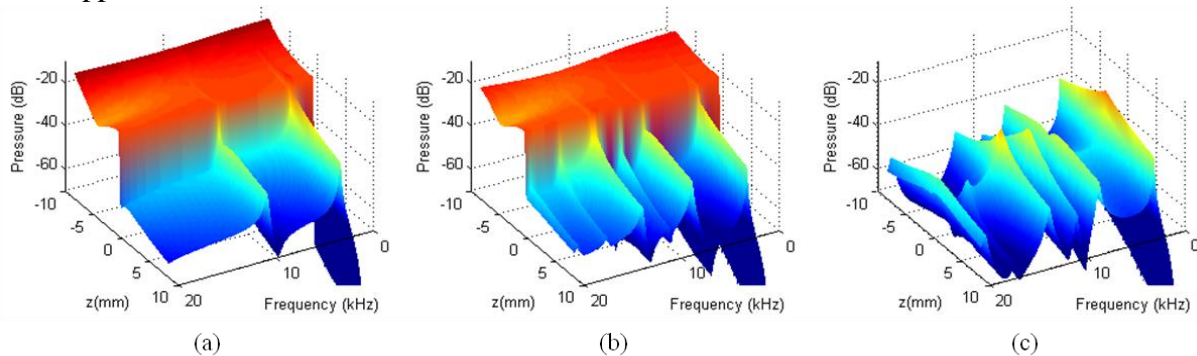


Figure 4. Sound pressure. Membrane (a), Membrane-Umbo forward (b) and reverse (c)

## 6   CONCLUDING REMARKS

A simplified numerical model to simulate the forward and reverse sound transmission mechanism has been build. This model will be used to adjust proper dimensions to facilitate the experiment. The presence of the umbo adds stiffness and mass to the system. Results prove that the effect of the mass is more significant, increasing the number of modes present in the range of frequency of interest. Comparing forward and reverse mechanisms the main difference is in the response on the side of the membrane where the stimuli is present.

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