TIMPANIC MEMBRANE PRESTRAIN EVALUATION BASED ON THE DYNAMIC REPSONSE

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ABSTRACT

Sound transmission in human hearing is easy to understand at low frequencies but at higher frequencies the tympanic membrane (TM) presents complex vibration patterns. They have been studied experimentally with holography and numerically with Finite Element models. These models need proper material properties to be valid. Particularly, the Young's Modulus of the TM is a key parameter. A broad range of values has been obtained depending on the methodology used (20 to 300 MPa). Controversy exists about its correct value. Passive prestrain can be argued as a cause of differences. It is present on dynamic tests but not in static tests.

In this paper, modal analysis is used to check the potential effect of prestrain as the cause of the higher stiffness observed. As direct model update is difficult due to the complexity of the system a methodology based on comparison of modal shapes with experimental patterns observed with holography will be applied to identify prestrain level.

Different FE models are employed to obtain modal values. Prestrain provides similar shapes but frequencies proportional to the prestrain (stiffness). Comparing with experimental patterns at high frequencies a prestrain value can be identify coherent with the properties commonly accepted (E=32 MPa).

1 INTRODUCTION

At low frequencies, sound transmission in human hearing is easy to understand. The Tympanic Membrane (TM) captures acoustic waves and by means of a piston-like motion transfers air sound pressure waves into the cochlea. However, at higher frequencies the TM motion is not so simple, appearing complex vibration patterns. These patterns have been studied experimentally with techniques as holography. Rosowski et al. [1] established a qualitative description based on the pattern observed and related with the range of frequency where they were present. They considered a simple pattern when only one maximum displacement zone was observed (below 2 kHz), complex pattern when more than one maximum appeared (2 to 8 kHz) and ordered pattern when a high number of maximum spread along the membrane (above 8 kHz).
The other alternative of study is numerical simulation. Finite Element (FE) models have been used as a tool to study the behaviour of the system [2,3]. Nevertheless, uncertainties regarding the material properties limit the conclusions. This is particularly significant in the case of the study of the TM. Many experimental works have been devoted to the determination of the Young's Modulus of the TM. Most of the results obtained are in the range 20 to 40 MPa, being the more accepted value 32 MPa. Some are based on tension tests on small samples and other use different indentation techniques. Fay et al. [4] suggested that these values could be underestimated; the main difference in their methodology was that it was based on the dynamic response of the TM. By using composite laminate theory and correlating experimental dynamic wave length patterns they suggested values from 100 to 300 MPa.
There exists controversy about the correct values for this parameter. One of the reasons of this higher stiffness value could be found on the potential effect of prestrain on the membrane. It would be present on dynamic tests but not in static tests. Passive prestrain has been named by several authors but no quantitative estimation has been made.
In the present paper, modal analysis is used to check the potential effect of prestrain on the dynamic response of the TM. Direct model update is difficult due to the complexity of the system [2,3] and the experiment itself [1,5]. So a methodology based on comparison of modal shapes with experimental patterns observed with holography will be applied to identify prestrain level.

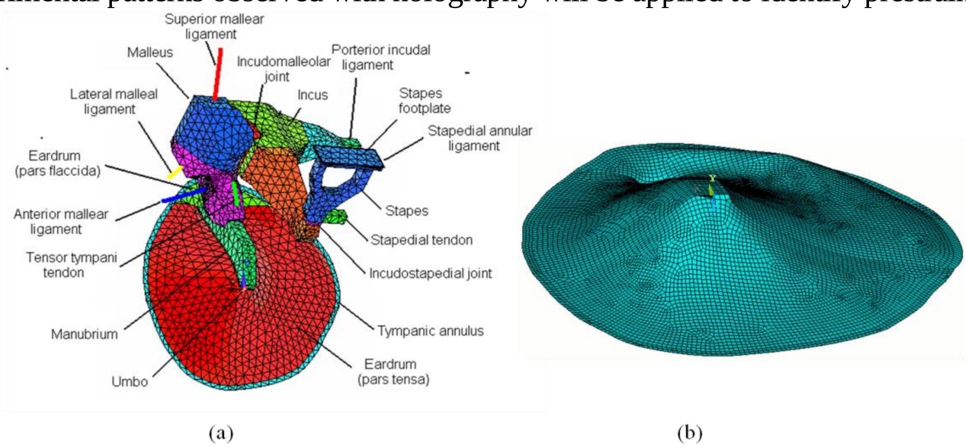

Figure 1. Finite Element Models. TOS model (a) and simplified model (b).

2 NUMERICAL METHODOLOGY

Two different FE models will be shown. The first one includes all the element of the middle ear, it will be referred as the Tympanic-Ossicular System (TOS) model (Fig 1a). The second one, only include the TM and the approximate effect of the manubrium (Fig 1b).

The TOS FE model was built with a geometric model of the different components, they were meshed and additional components and boundary condition added. The anatomic measures and functional properties were based on published data [2,3]. TM Young Modulus is 32 MPa.
Regarding the simplified model (Fig. 1b), most of the component has been removed. The connection with the manubrium is modelled with shell elements but the mechanical properties represent the inertia and stiffness of the ossicular chain. These equivalent properties has been obtained comparing with the TOS model. A key difference is that the membrane has been meshed with a higher number of elements to increase the accuracy at high frequency.

3 MODAL ANALYSIS

A modal analysis of the TOS was made as reference. Some selected mode shape has been drawn in Fig. 2a. Different types of modes are present, some reflect a TM vibration pattern and the classic piston-like motion (modes 11 and 13). Modes 14 and 25 correspond to the transition to complex pattern and mode 29 represent the ordered pattern. The results of the modal analysis of the simplified model are on Fig. 2b. It can be seen the equivalence between both system at certain modes (with different numbering). Mode 7 is the first complex patterns. Modes 11 represents the transition to ordered pattern. Finally, mode 50 correspond clearly to the ordered pattern. The small element size used in this model to mesh the TM captures these modes accurately. At this frequency range, the absence of the ossicular chain has a low influence, so for the purpose of the present study this simplified model is acceptable.

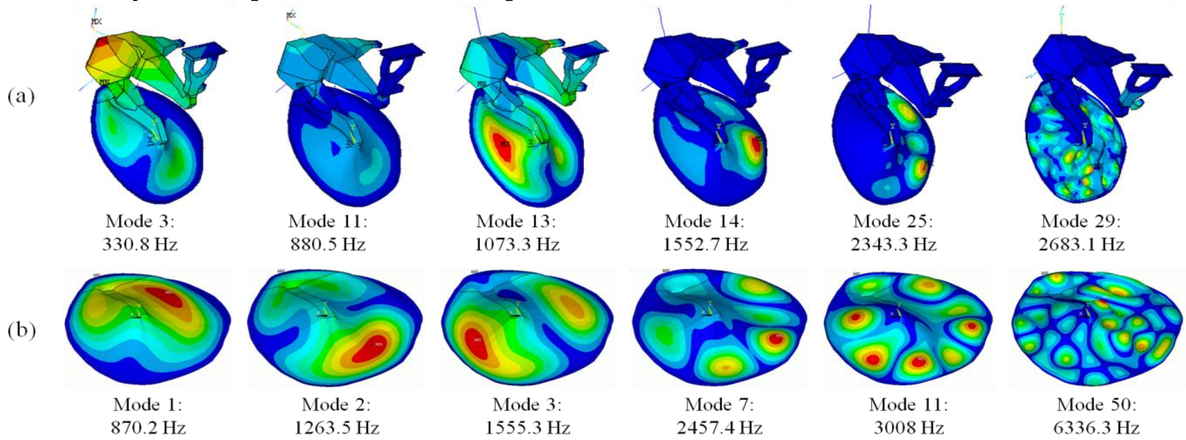

Figure 2. Modal shapes. TOS (a) and simplified model (b)

4 RESULTS

The simplified model has been used to evaluate the influence of passive prestrain in the membrane. It is an aspect of the system with direct influence on the natural frequencies. An homogeneous isotropic strain has been considered for the whole membrane, ranging from 0.1% to 1% ($\varepsilon_{11} = \varepsilon_{22} = 0.001$-$0.01$, in the plane of the TM and $\varepsilon_{33} = -2\varepsilon_{11}$). Modal analysis has been repeated for different values of prestrain. Modal shapes are similar but frequencies increase proportionally to the prestrain level. Natural frequencies are plotted in Fig. 3 in terms of the mode number. We can see how the reference values (E = 32 MPa, black triangle, no prestrain) for the simplified model are coincident with the complete system (TOS, white circle).
Observing these results at lower frequencies is difficult to establish clear differences. But, if we focuses on the higher modes, some distinctions can be done comparing with the experimental observation. Considering mode 50 as a reference, this type of pattern has been detected in human at frequencies above 8 kHz [1], in the case without prestrain, this pattern appears at 6 kHz that

could be considered very low and erroneous. Following this, the case pst = 0.3% could be considered more realistic. This observation cannot be considered a closed result as the increase of the elastic modulus has the same effect. A different combination of elastic modulus and prestrain provides similar responses. However, it point out to the dynamic analysis as a tool to clarify these effect instead of static tests. Modal shapes comparison is a limited first step procedure that must be followed by the direct numerical-experimental comparison of the response of the system including the fluid interaction. Although some methodological aspect must be solved first [5].

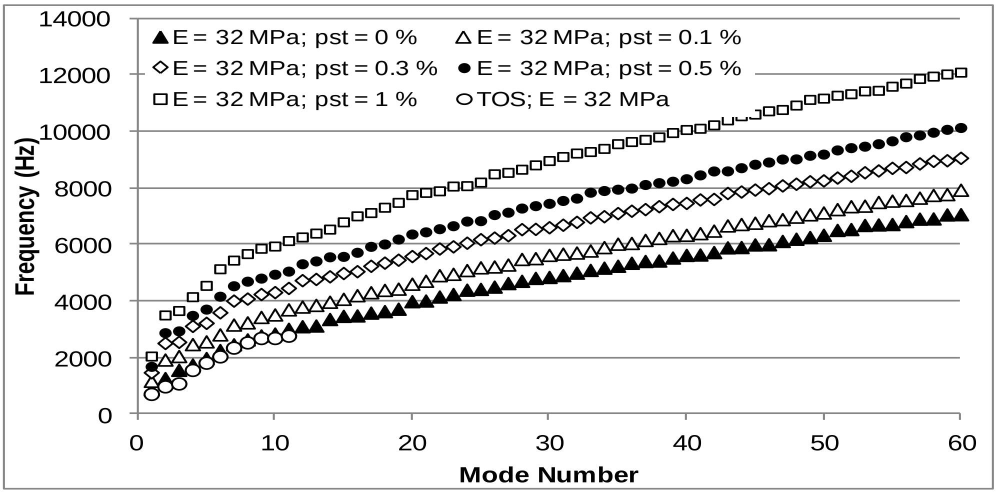

Figure 3. Tympanic Membrane modal frequencies with different prestrain (pst) level

5 CONCLUDING REMARKS

Supported on experimental observation with holography techniques, prestrain has been evaluated on the TM. It causes an stiffness increase difficult to distinguish from the effect of the elastic modulus of the material. This could be the reason for the lack of agreement of its estimation.

Comparing modal shapes with experimental patterns, the appearances of complex patterns at higher frequencies can be used to check a valid value for the properties assigned to the model.

Modal shapes comparison can be considered an starting step to be followed by direct numerical-experimental comparison of the response of the system.

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