Using DIC and the VFM to determine eardrum stiffness

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Abstract. The human eardrum, or tympanic membrane (TM), is a thin and cone-shaped membrane. It transforms acoustical sound energy into vibrations of the middle ear bones, called ossicles. While the TM has been investigated intensively since the nineteen hundreds, the stiffness of the TM is still debated. In part, the complicated shape and positioning make *in-situ* determination difficult. However, the virtual fields method (VFM) allows for determining the properties of materials with difficult access, provided proper virtual fields and high-quality full field data are present. During the conference, we will highlight our current experimental setup in which we use digital image correlation (DIC) to study the dynamic motion of the TM. Moreover, we will discuss our current developments in the VFM to determine the constitutive parameters of the TM.

Possible Sessions

30. Virtual Fields Method **4.** Biomaterials and Biomechanics **12.** Medical applications

Introduction

Several experimental approaches have been used to determine the constitutive parameters of the TM. Isotropic values between 20-40 MPa were first determined on cut-out rectangular strips under uniaxial tension [1,2]. However, the TM has radial and circumferential fibres embedded in its surface, which indicates that an orthotropic constitutive relation is more realistic. Therefore, orthotropic tests were performed, which resulted in values between 45-59 MPa and 34-57 MPa in the radial and circumferential direction, respectively [3,4]. Finite-element (FE) modelling has also been used, in which the material parameters of the model are adjusted to match experimentally measured vibration curves [5]. However, many a-priori assumptions need to be made during FE-model construction, making accurate determinations difficult.

The VFM also allows for stiffness determination, and has several benefits compared to the approaches mentioned above. For example, the need for cut-out rectangular samples is negated since the VF themselves can remove unknown boundary effects, such as the connection to the ossicles. However, full field strain data of high quality is required. DIC is a suitable technique to acquire such strain fields, provided visual access to the TM can be achieved.

We will present our current DIC setup to measure TM displacements and corresponding strains. We will discuss general best-practices regarding DIC and our findings concerning the dynamic behaviour of the TM. Additionally, we will detail our VF approach to determine the constitutive properties of the TM so the full process from experimental acquisition to constitutive identification can be understood.

Experimental steps & results

All experiments were performed on cadaveric donor material. The ear canal was removed until visual access was acquired of the TMs lateral surface. The TM surface was then stained with a fluorescent dye using an airbrush. The sample was then mounted against a cavity connected to a sound speaker. A pulsed laser (532 nm) illuminated the TM phase-locked with respect to the incoming soundwave.

A sound level of 94 dB (1 Pa RMS) results in a displacement of only 200 nm. The resolution of DIC is insufficient at these sound levels to determine the resulting strains. Therefore, sound levels of 134 dB (100 Pa) and 140 dB (200 Pa RMS) were used in the experiments. In Fig. 1, the measured strains for a pressure level of 134 dB can be seen for three different incident frequencies of sound. The TM edge, and where it connects to the hearing ossicles is denoted by the dotted lines. Figs. 1A-I show similar strain values of up to 1.25%. Noteworthy is that Figs. 1D-F, for a frequency of 791 Hz, show a higher strain value and displacement (not shown), indicating that this sample had a resonance around this frequency.

To compute orthotropic stiffness parameters of the TM, our VF approach used previously [6] to determine isotropic values of the TM will be expanded. By using a recently published approach [7], VFs can be created more readily to identify all orthotropic material parameters. In Table 1, our intermediate results based on simulated FE data are given.

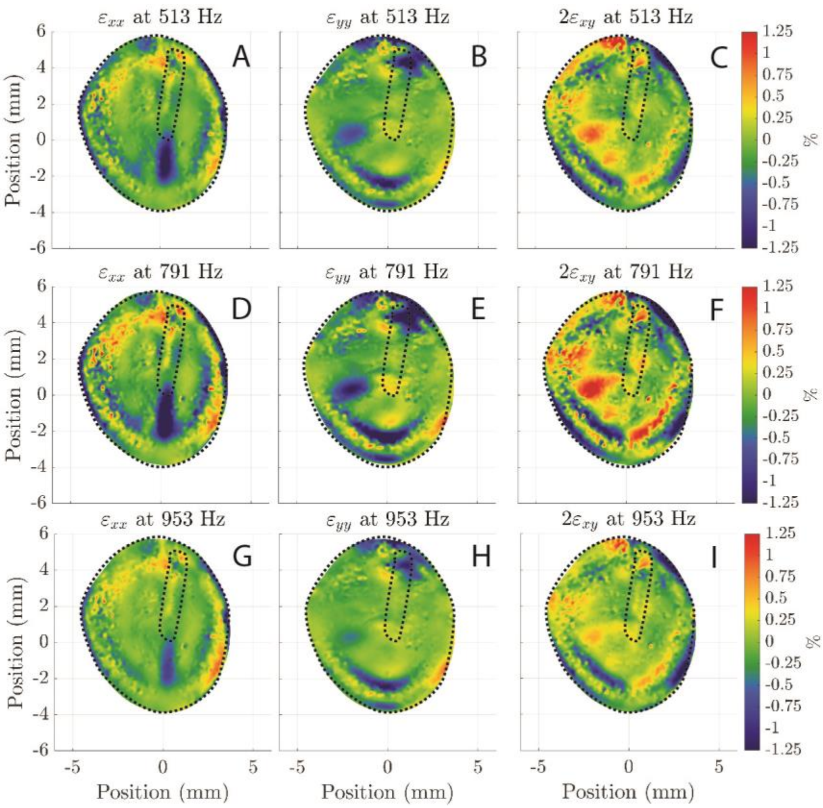

Figure 1. TM strains measured at frequencies of 513 Hz (A-C), 791 Hz (D-F), and 953 Hz (G-I), respectively for a sound pressure level of 135 dB. The frequency of 791 Hz shows largest strains and corresponding displacement amplitudes, indicating that 791 Hz was around the TM's resonance frequency. Dotted lines denote the TM boundary and the location of the hearing ossicles.

	Reference value	Identified value	Error (%)
Radial Youngs modulus	20 [MPa]	20.15 [MPa]	0.74
Circumferential Youngs modulus	15 [MPa]	15.57 [MPa]	3.83
Poisson's ratio	0.3	0.299	-0.39
Shear modulus	1 [MPa]	1.06 [MPa]	2.59
Damping Coefficient	0.2	0.2	1.07

Table 1. Identified stiffness values of a human eardrum based on a FE simulation at 679 Hz.

Conclusion

Using DIC, full field strain measurements of a vibrating eardrum are possible. Using the VFM, the eardrums orthotropic stiffness values can be determined.

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