Study of the mechanical properties of the avian middle ear by optical interferometry and finite element modeling

P. Muyshondt[1a], D. De Greef[1], J.Soons[1], and J.J.J. Dirckx[1]

[1]University of Antwerp, Laboratory of Biomedical Physics, Groenenborgerlaan 171, B-2020 Antwerp, Belgium

[a]pieter.muyshondt@uantwerpen.be

Abstract

Introduction

In all mammals, the middle ear is made up of an eardrum and three hearing bones we call ossicles. These ossicles function as an impedance match between the air in the outer ear and the fluids in the cochlea of the inner ear. Acoustic energy is absorbed by the eardrum, converting it into mechanical vibrations, and the ossicles transports these vibrations in a very efficient way towards the inner ear. The mobility between the ossicles plays a very important role in protecting the cochlea from quasi-static pressure differences [1]. Birds on the other hand have only one ossicle, called the columella, which directly connects the eardrum to the inner ear. Despite this much simpler mechanical constitution, the avian ear is almost as efficient as its mammal counterpart [2], and somehow it is able to cope with much larger quasi-static pressure changes than most mammals have to deal with, as they often bridge large altitude differences while flying. This knowledge makes the investigation of the avian middle ear potentially very meaningful, since it could provide insights that can improve the design and implantation of prosthetic ossicle replacements in humans such as a TORP (Total Ossicle Replacement Prosthesis), which resemble the avian columella: these prosthesis are involved with defects such as large static displacements due to quasi-static pressure differences [3]. In this paper we present the study of the mechanical properties of this system by means of optical interferometry experiments and finite element modeling.

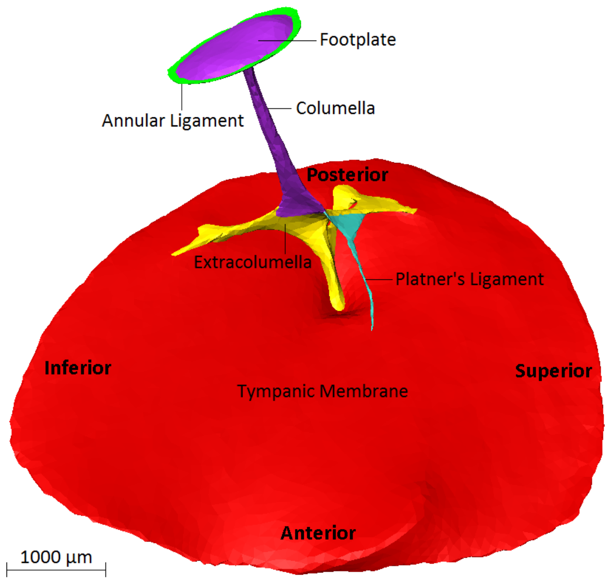

Figure 1: Geometrical surface model of the middle ear of a mallard duck, reconstructed from µCT measurements. The different components and anatomical orientations are indicated [4].

Experimental and numerical methods

To create the finite element model we made use of COMSOL for which the geometry (presented in Fig. 1) is extracted from stained micro-CT measurements with a resolution of 7.5µm [5]. In this model, the transmission of incident quasi-static and acoustic pressures over the ear is simulated by a uniform mechanical load at the lateral eardrum surface. The impedance force caused by the inner ear fluids is modeled by a viscoelastic spring foundation exerted at the columellar footplate [6]. To model the linear response of the middle ear structures to harmonic pressures, the calculations are performed in the frequency domain. As the mechanical parameters of all middle ear components are unknown in advance, they must first be determined by comparing the model to experimental results. Therefore, a series of experiments on optical interferometry were performed on the middle ear of a mallard duck to measure the vibrational response of the system under acoustic stimulation. First of all, we used digital stroboscopic holography to measure the full-field vibrational displacement of the eardrum at different stimulation frequencies. These experiments were then complemented by laser Doppler vibrometry to measure the single-point central footplate velocity. Observed phase variations across the eardrum's surface in the holography results suggest the presence of internal energy losses in the membrane due to damping [7]. Therefore, a viscoelastic characterization of the model is chosen, based on a complex Young's modulus with loss factor to account for damping.

Model optimization and results

As already observed, the mechanical parameters of the system are still unknown. To determine these properties, an inverse engineering routine is constructed in which the model output is optimized to the experimental results. Therefore we make use of the Matlab SUrrogate MOdeling Toolbox (SUMO) [8], in which an objective function is evaluated, defined as

$$\chi^2(p) = \sum_i \left[f_{\mathrm{mod}}(x_i, p) - f_{\mathrm{exp}}(x_i)\right]^2 \tag{1}$$

In this equation, f represents the model and experimental output respectively, p the set of optimized model parameters, which we choose by a sensitivity analysis, and x_i a series of dependent variables. When we use holography as experimental input, f represents the eardrum displacement amplitude and phase, both normalized, and x_i the spatial eardrum coordinates. In the case of vibrometry as input, f is the central-point footplate velocity and x_i the applied stimulus frequencies. Optimal values for different isotropic and orthotropic material parameters were determined by minimizing Eq. 1, resulting in a good correspondence of the vibrational patterns between the model output and the holography results, as shown in the example of Fig. 2.

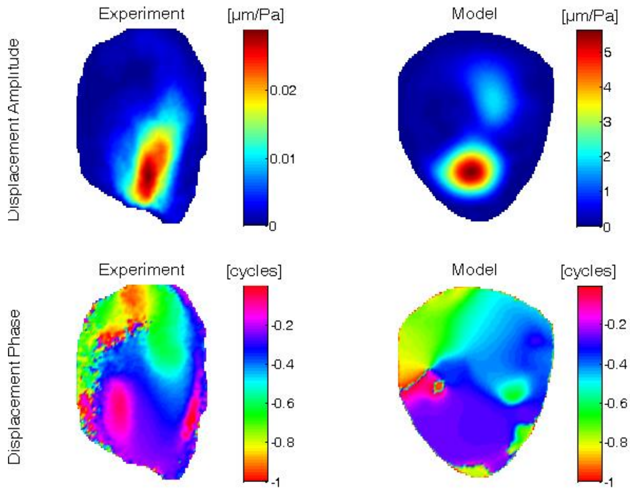

Figure 2: The displacement amplitude (top) and phase (bottom) of the eardrum at 1600 Hz, compared for the holography results (left) and the optimized model (right) [4]. The optimized Young's moduli *E* were found to be [E_{TM}, E_{EC}] = [40.3, 39.6] MPa. (TM = tympanic membrane, EC = extracolumella).

References

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