Determination of the Mechanical Properties in the Avian Middle Ear By Inverse Analysis

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Abstract

Whereas the middle ear of all mammal species contains three hearing bones or ossicles, birds only feature one ossicle, the columella. Despite this less advanced mechanical constitution, the hearing capacity of birds is not significantly worse than mammals [1, 2], and is adapted to operate under very diverse atmospheric circumstances. This makes the investigation of the avian middle ear potentially very meaningful, since it could provide knowledge that can improve the design and implantation of prosthetic ossicle replacements in humans such as a TORP (Total Ossicle Replacement Prosthesis). In this paper we present a finite element model of the avian middle ear using COMSOL Multiphysics® simulations.

To create the finite element model, we made use of the Structural Mechanics Module in COMSOL, for which the geometry (presented in Figure 1) is extracted from stained micro-CT measurements with a resolution of 7.5µm [3]. The model simulates the transmission of incident acoustic waves on the tympanic membrane through the middle ear structures to the oval window of the cochlea. At the oval window acoustic waves are generated in the fluid of the inner ear. In this sense, the middle ear functions as an acoustic impedance matching system between air and the inner ear fluid. As a first approximation, the incident acoustic waves are modeled by a uniform harmonic load applied to the outer eardrum surface, whereas the acoustic impedance load caused by the inner ear fluid is modeled by a viscoelastic spring foundation at the columella footplate [4].

To model the linear response of the middle ear structures to these harmonic loads, the calculations are performed in the frequency domain. In addition a series of optical interferometric experiments were performed on an acoustically stimulated middle ear, including stroboscopic digital holography to measure the full field displacements on the entire eardrum, and laser Doppler vibrometry to measure the vibration velocity of the columella footplate in a single point [5]. 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 [6]. Therefore, a viscoelastic characterization of the model based on a complex modulus with loss factor damping is chosen.

Since the mechanical parameters of the system are unknown, they are optimized by performing an inverse analysis routine using the experimental results. This is achieved by use of the MATLAB® Surrogate Modelling Toolbox (SUMO) [7], in which an objective function is evaluated, defined in Figure 2, with ri the spatial coordinates on the eardrum, p the model

parameters, M the magnitude and ϕ the vibration phase, both normalized. The subscripts 'mod' and 'exp' stand for the model and experimental results. Optimal values for the most influential isotropic or orthotropic material parameters are then determined by minimizing the equation of the object function, resulting in a good correspondence between the vibrations patterns of the model results and the holography measurements.

Reference

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Figures used in the abstract

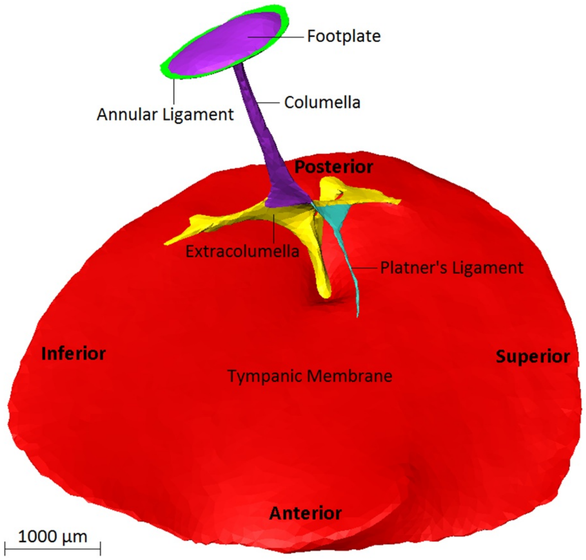

Figure 1: Geometrical surface model of the middle ear of a mallard duck, reconstructed from µCT measurements. The different components and anatomical orientations are indicated.

$$R^2(p) = \sum_{i=1}^{n}\left[\left(M_{\mathrm{mod}}(r_i,p) - M_{\mathrm{exp}}(r_i)\right)^2 + \left(\phi_{\mathrm{mod}}(r_i,p) - \phi_{\mathrm{exp}}(r_i)\right)^2\right]$$

Figure 2: Equation of the used object function.