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

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Introduction: The avian middle ear is a biomechanical system that serves as an impedance match between the air-filled outer ear and the fluid-filled inner ear. It is made up of one ossicle, the columella. To determine its mechanical parameters, an inverse analysis is performed by comparing the outcome of a finite element model to experimental results.

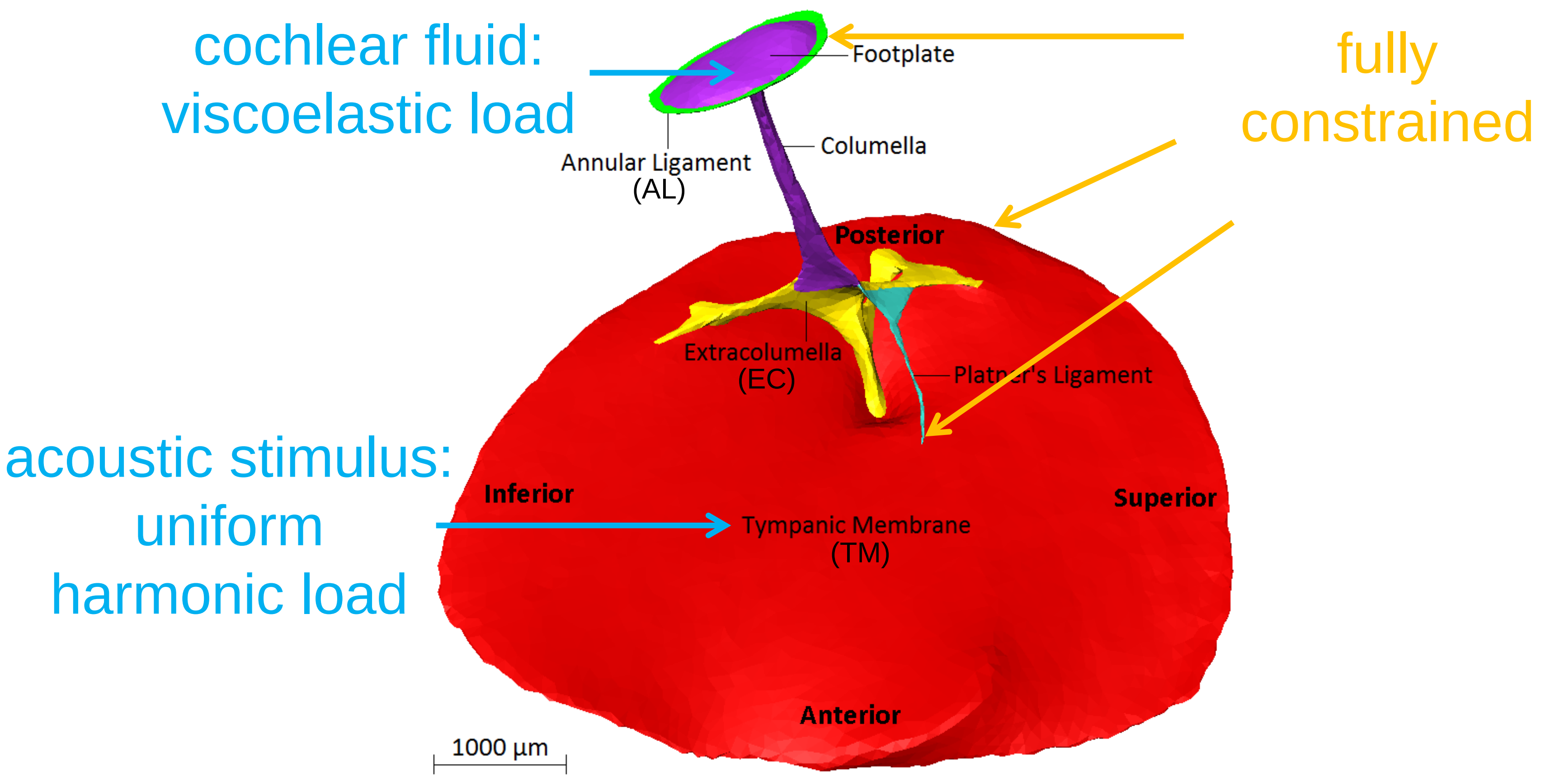

Figure 1. The different components in the avian middle ear [1]. The boundary conditions in the numerical model are indicated.

Numerical model: The model is built with the Structural Mechanics Module and solved in the frequency domain, using a viscoelastic characterization by a complex Young's modulus E with loss factor η_s [2]. The geometry is extracted from µCT scans on a mallard duck [3]. The tympanic membrane and the annular ligament are fully constrained at their surroundings, as well as the end of Platner's ligament. The acoustic stimulus is modeled by a uniform harmonic load of 1 Pa at the outer eardrum surface, and the cochlear fluid impedance by a viscoelastic spring foundation at the footplate [4]. All boundary conditions are shown in Fig. 1. Shell elements are used for the TM and solid elements for the remaining components. The initially used material parameters, listed in Table 1, were chosen isotropic.

Component	ρ [kg/m³]	E [MPa]	η_s	ν
TM	1.2E3	20	0.078	0.3
Columella	2.2E3	1410	0	0.3
Extracolumella	1.2E3	39.2	0.078	0.3
Platner's lig.	1.2E3	21	0.078	0.3
Annular lig.	1.2E3	0.0412	0.078	0.3

Table 1. Literature-based starting parameters used in the model. ρ = mass density and ν = Poisson's ratio.

Inverse analysis: Under acoustic stimulation at different frequencies ω, the full-field eardrum vibration is measured with stroboscopic digital holography (SDH), and the single-point footplate velocity V with laser Doppler vibrometry (LDV) [1]. The mechanical parameters p are then determined by minimizing objective functions (1) & (2) between model and experiment, using the Matlab Surrogate Modeling Toolbox [5] and the LiveLink for Matlab. Notice that the magnitude M is normalized in this computation.

$$f^2(p) = \sum_i \left(M_{\mathrm{mod}}(r_i, p) - M_{\mathrm{exp}}(r_i)\right)^2 + \left(\phi_{\mathrm{mod}}(r_i, p) - \phi_{\mathrm{exp}}(r_i)\right)^2 \quad \text{SDH – (1)}$$

$$f^2(p) = \sum_i \left(V_{\mathrm{mod}}(\omega_i, p) - V_{\mathrm{exp}}(\omega_i)\right)^2 \quad \text{LDV – (2)}$$

Results: Different Young's moduli E, either isotropic (TM, EC & AL) or orthotropic (r radial & θ circumferential direction in the TM plane [6, 7]), were determined in the inverse analysis (see Table 2 & Fig. 2-4).

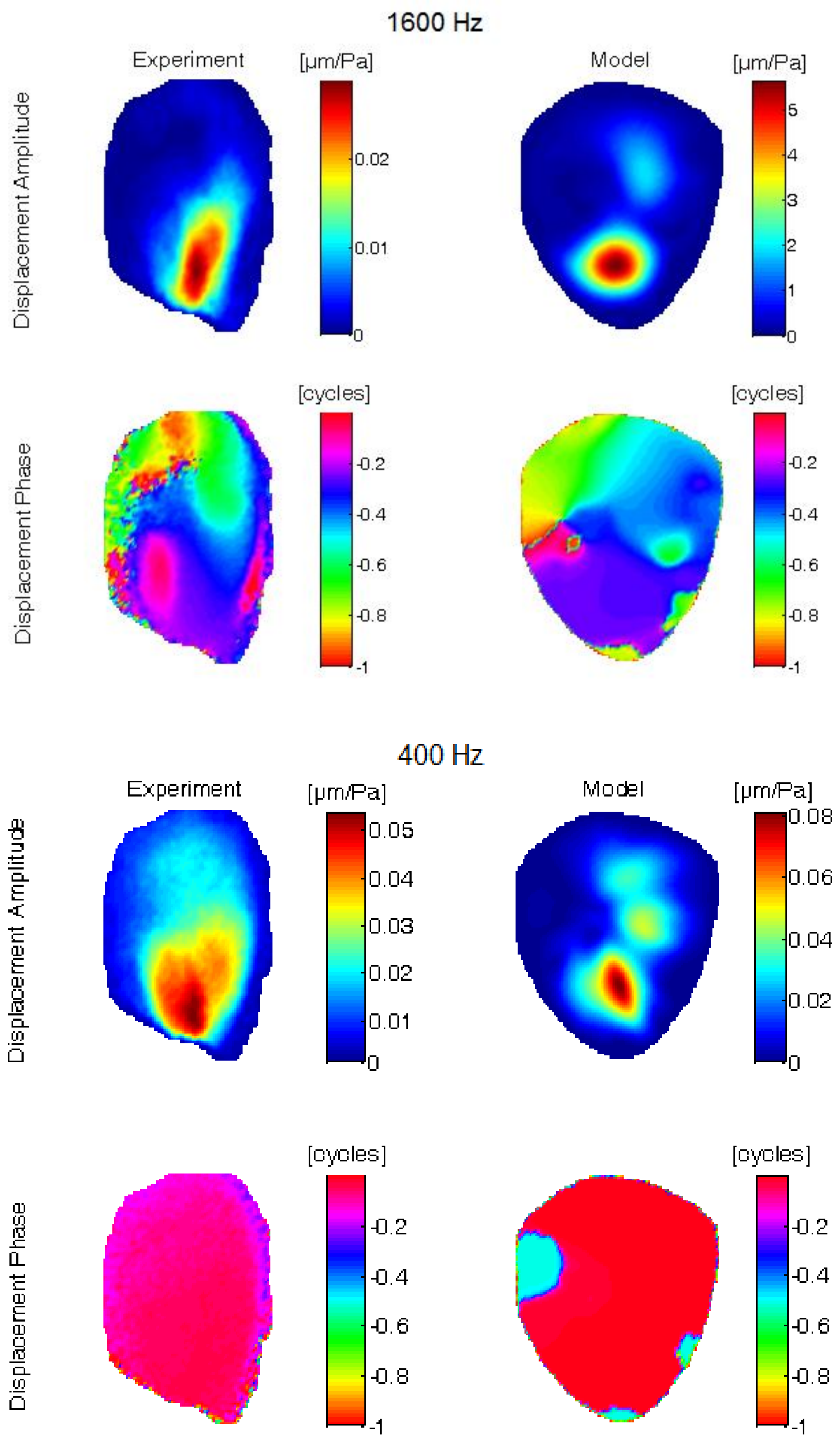

Figure 2. M- & ϕ-maps of experiment v. model for the obtained parameter values.

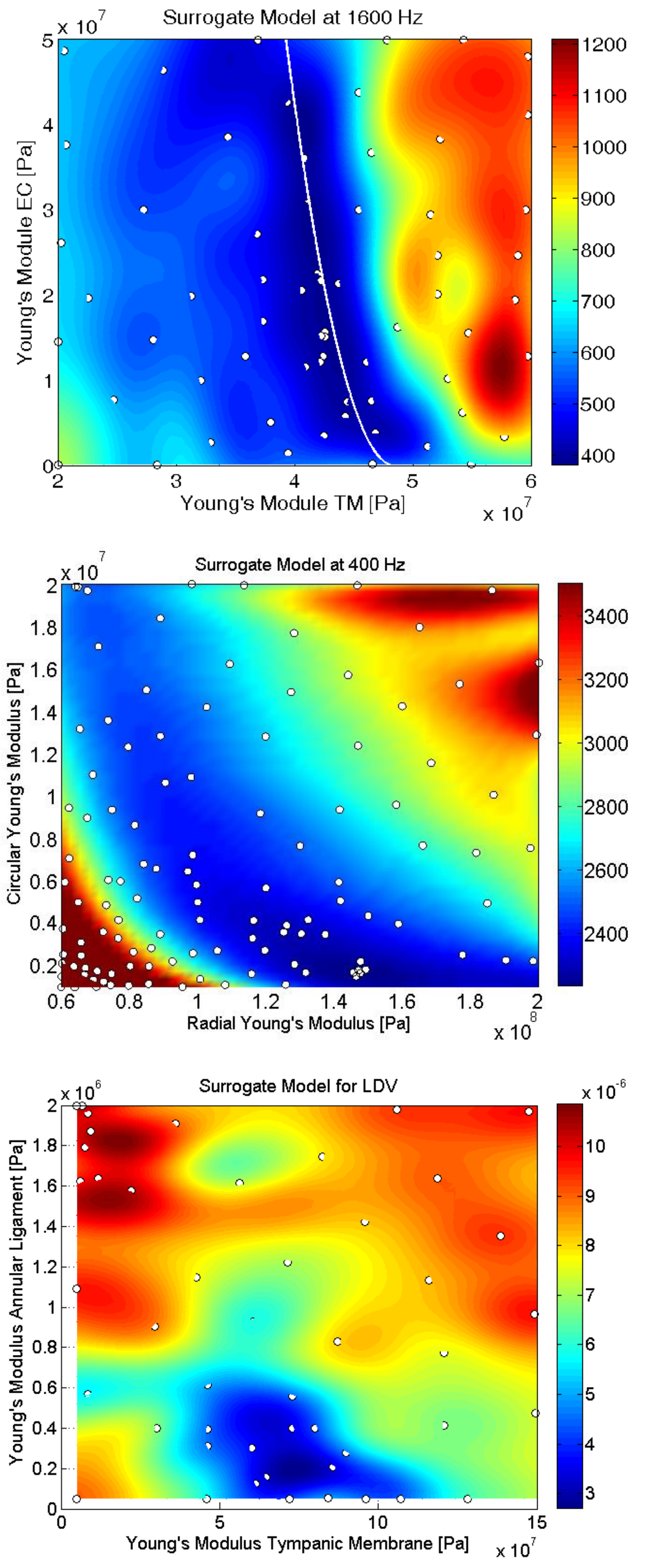

Figure 3. Surrogate models of objective functions (1) & (2) in which minima were identified.

Exp.	ω [Hz]	p	[MPa]
SDH	1600	E_{TM}	40.3
		E_{EC}	39.6
SDH	400	E_r	146
		E_θ	1.52
LDV	Fig. 4 **bold**	E_{TM}	64.5
		E_{AL}	0.156

Table 2. Calculated parameter values from inverse analysis, based on model & experimental results.

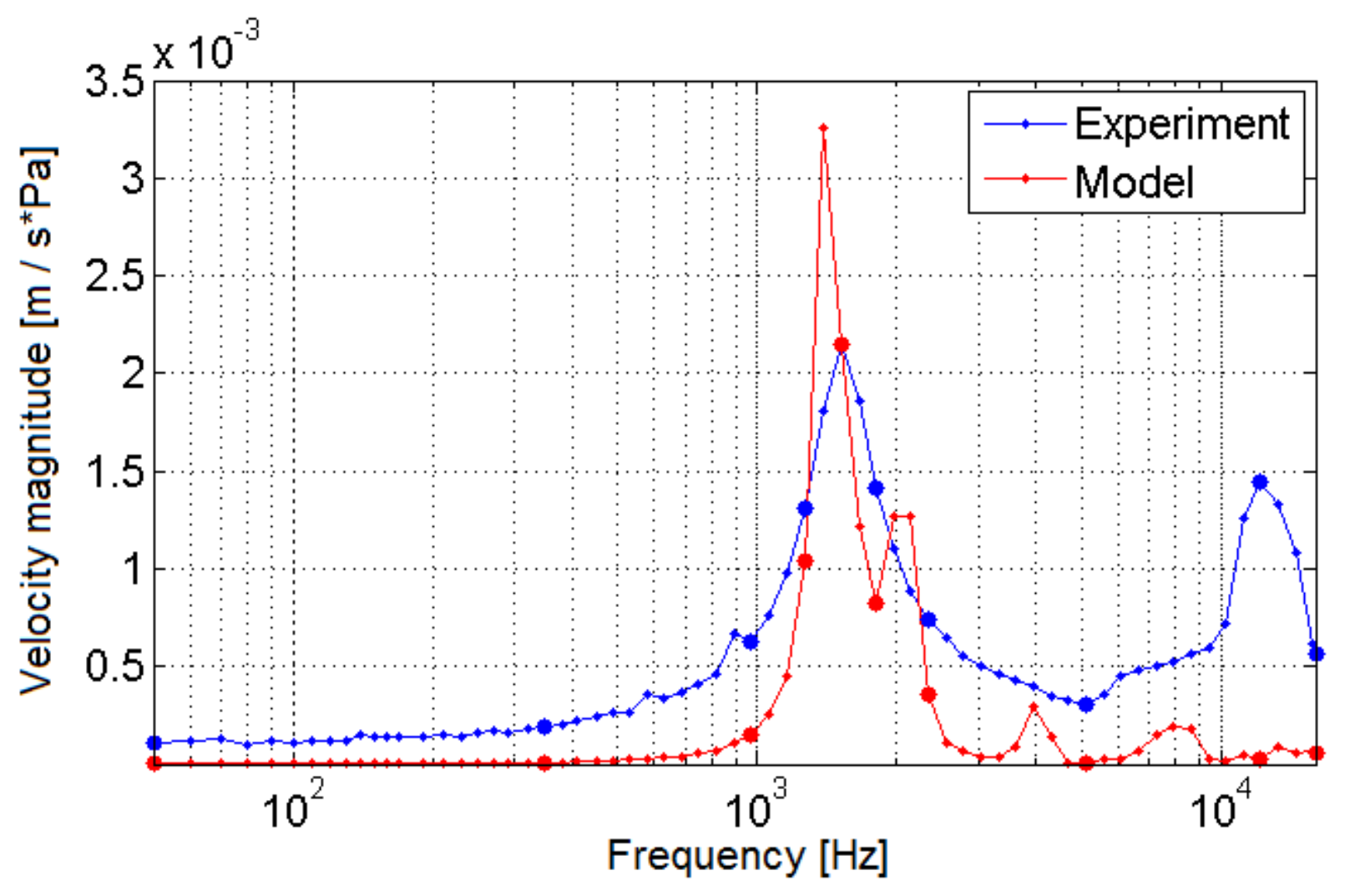

Figure 4. Footplate velocity for experiment v. model.

Conclusions: This study provides new insights in the elastic properties of the avian middle ear, and can be helpful to optimize human ossicle prostheses. In the future, acoustic-shell interaction will be incorporated, and also new experiments, sensitivity & uncertainty analyses will be done.

References:

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