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

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Bimef
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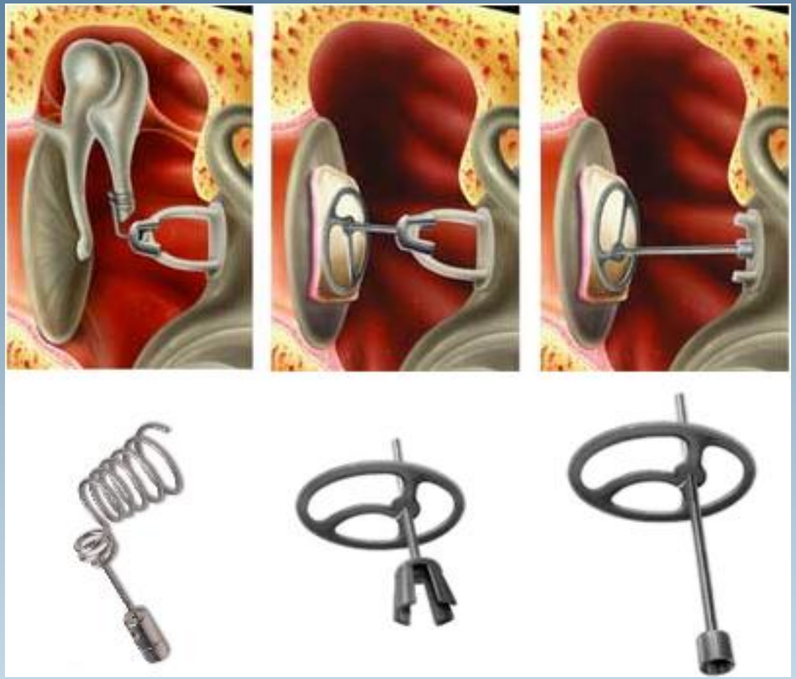
COMSOL CONFERENCE
2014 CAMBRIDGE

Motivation

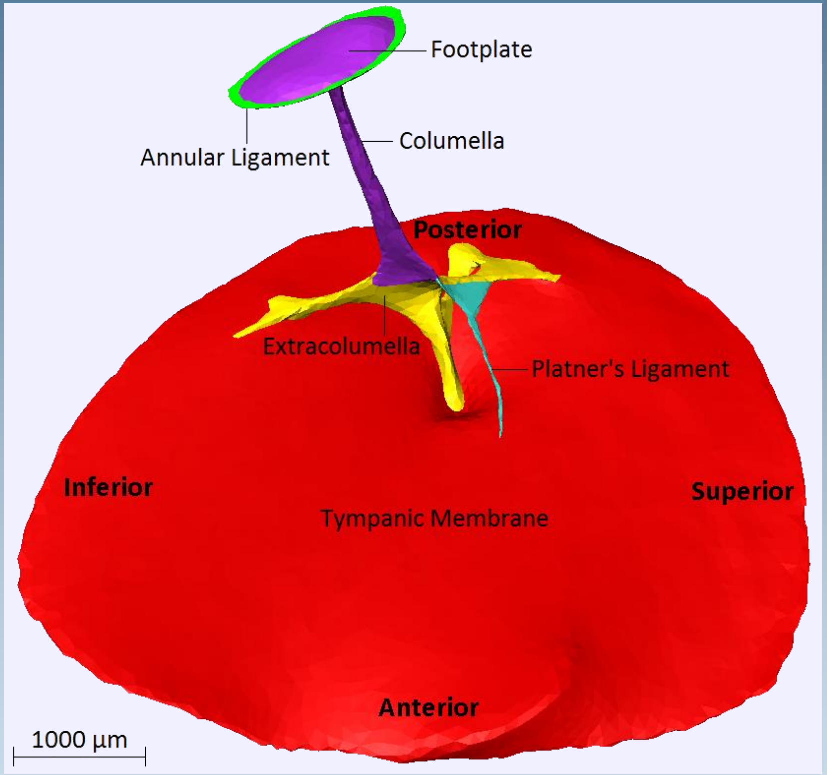
Mammal

Middle ear prostheses

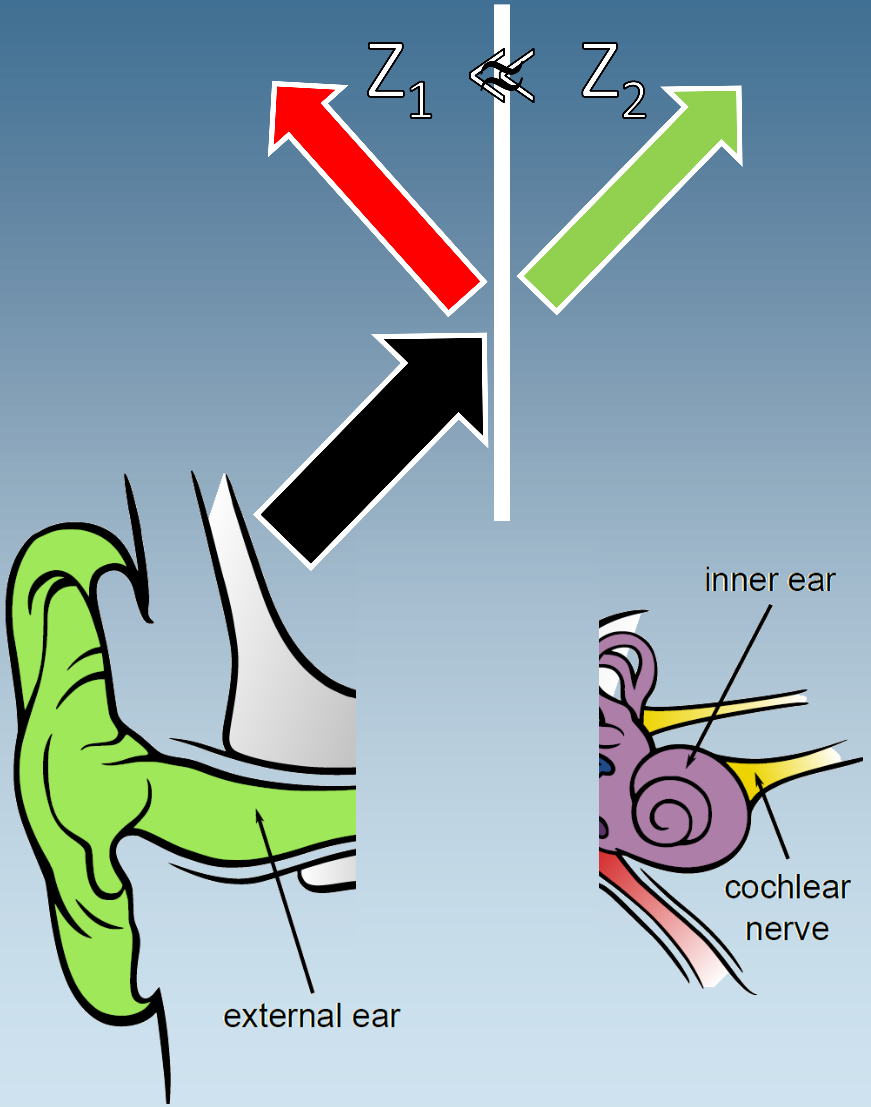


TORP (Total Ossicular Replacement Prosthesis)

Bird



Acoustic Impedance

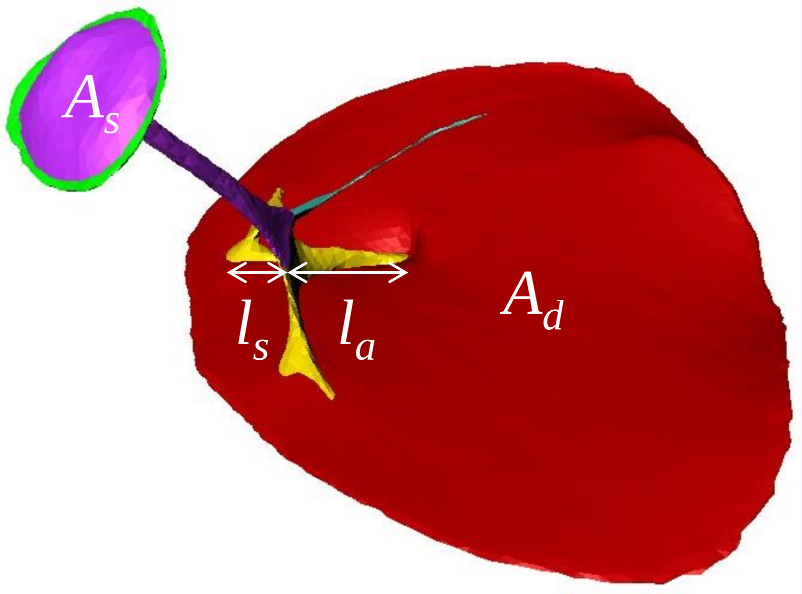


The Avian Middle Ear: Principles

- Impedance matching
  - Hydraulic lever

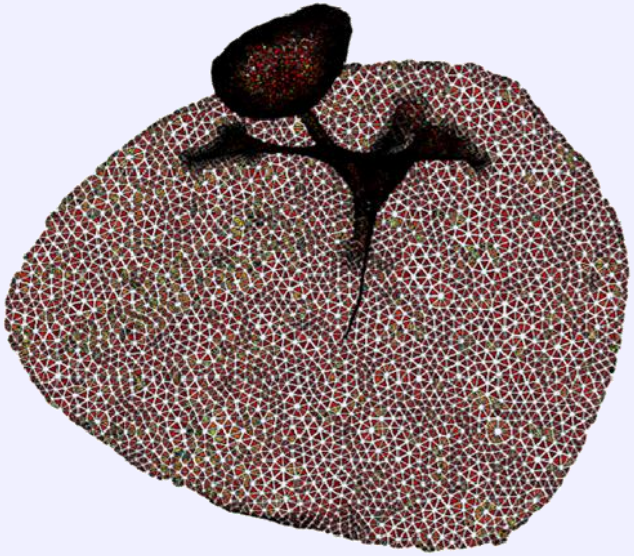
$$\frac{p_s}{p_d} = \frac{A_d}{A_s}\frac{l_a + l_s}{l_s}$$

  - Ossicular lever
    - Angle of columella!



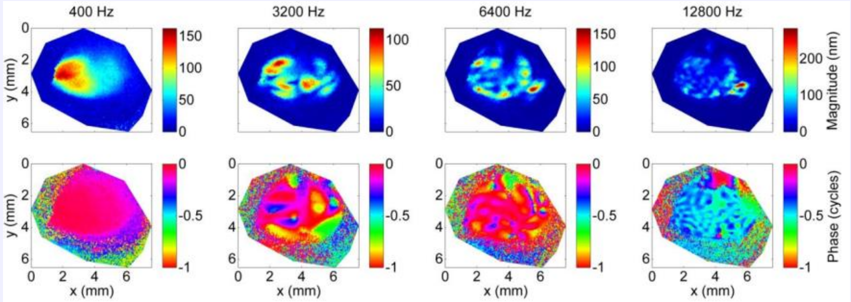
Finite Element Model

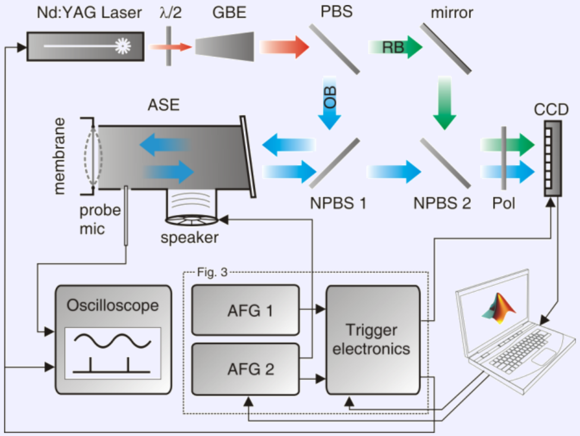
- Geometry
  - µCT scans of mallard duck
- Computations
  - Structural mechanics
  - Frequency domain
- Material
  - Description: viscoelastic (literature values)
- Loads
  - Sound waves: uniform load at eardrum
  - Cochlear fluid: spring foundation at footplate
- Meshing
  - Solid & shell elements



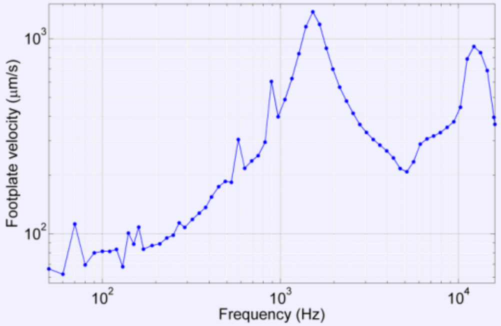
Experimental Validation

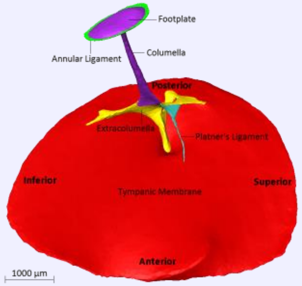
- Stroboscopic digital holography
  - Full field: eardrum displacement

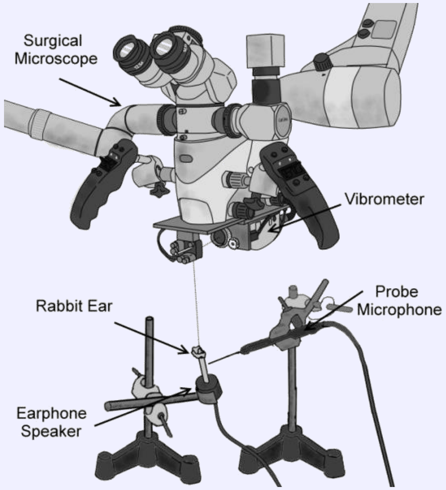




- Laser Doppler vibrometry
  - Single point: footplate velocity







Model Optimization

- Sensitivity tests
  - Relative influence of parameters?
- Inverse analysis
  - SUMO toolbox (SUrrogate MOdelling) & LiveLink for MATLAB
  - Minimize objective function

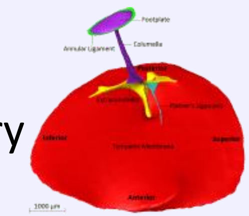
Holography: $$R^2(p) = \sum_{i=1}^{n} \left[\left(M_{\mathrm{mod}}(r_i, p) - M_{\mathrm{exp}}(r_i) \right)^2 + \left(\phi_{\mathrm{mod}}(r_i, p) - \phi_{\mathrm{exp}}(r_i) \right)^2 \right]$$

Vibrometry: $$R^2(p) = \sum_{i=1}^{n} \left(V_{\mathrm{mod}}(\omega_i, p) - V_{\mathrm{exp}}(\omega_i) \right)^2$$

Model Optimization

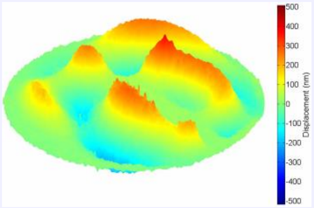
Parameters ?

Geometry



MODEL OUTCOME

EXPERIMENTAL DATA



Objective function

Max iterations

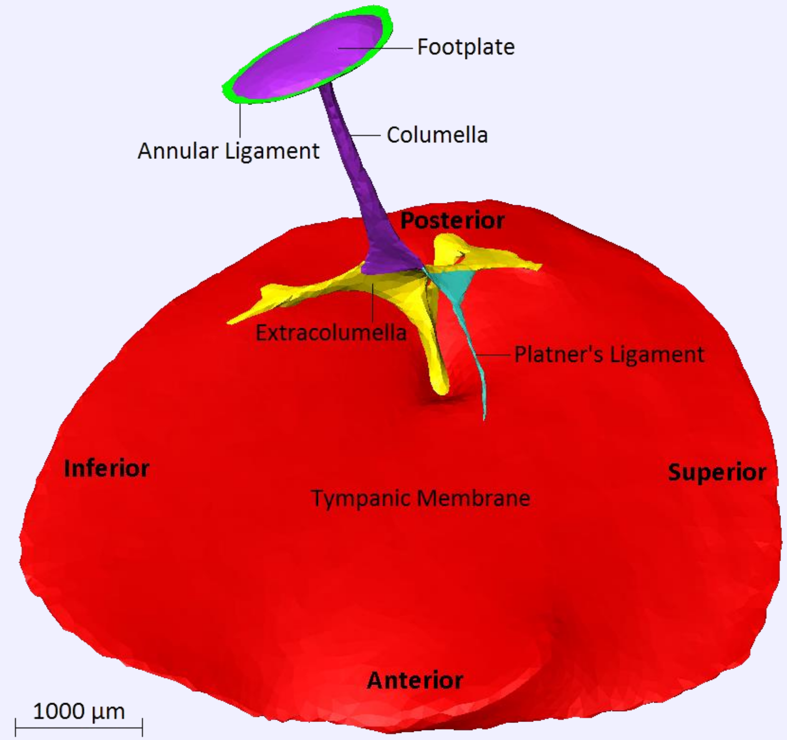
NO

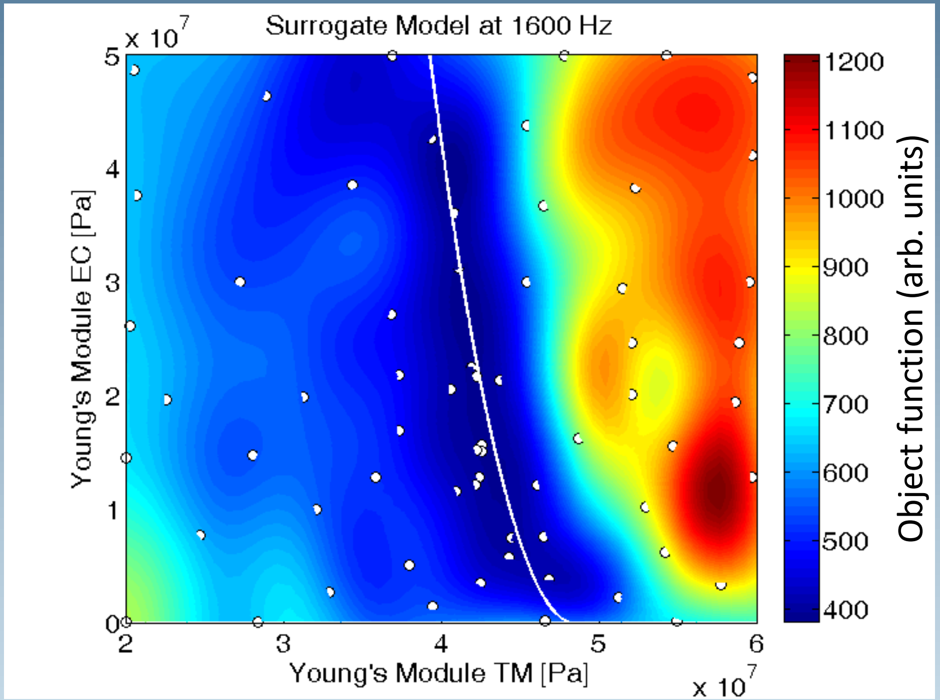
YES

New parameters based on previous results

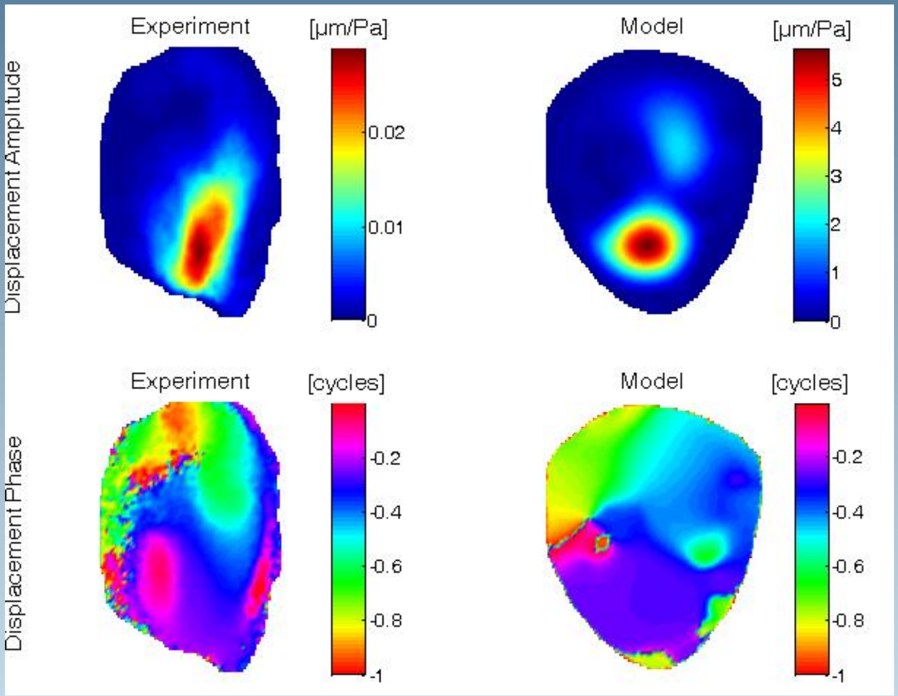
Holography

- 1600 Hz
  - $[E_{TM}, E_{EC}]$ = [40.3, 39.6] MPa





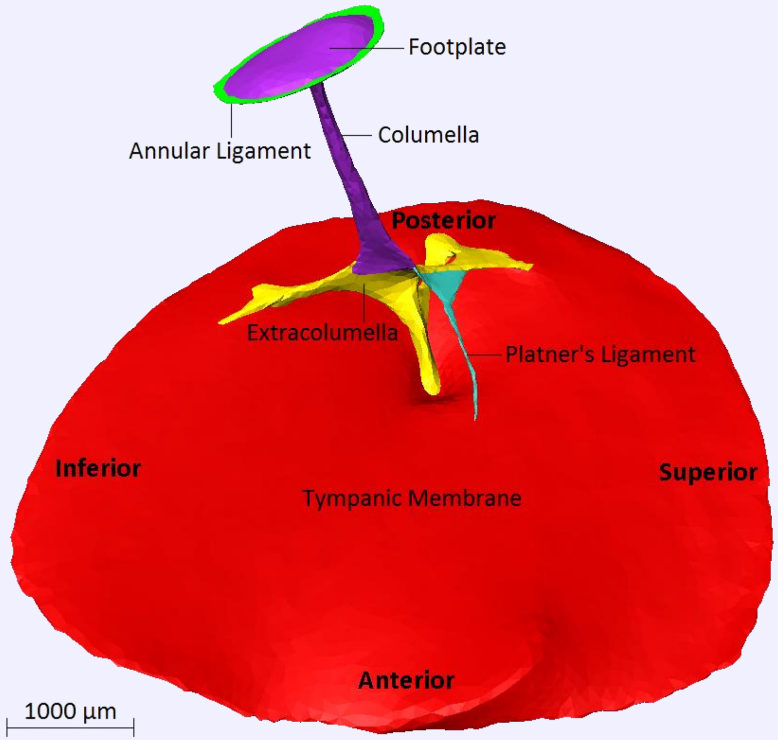
Surrogate Model at 1600 Hz
x 10^7
Young's Module EC [Pa]
Young's Module TM [Pa]
x 10^7
Object function (arb. units)
1200
1100
1000
900
800
700
600
500
400



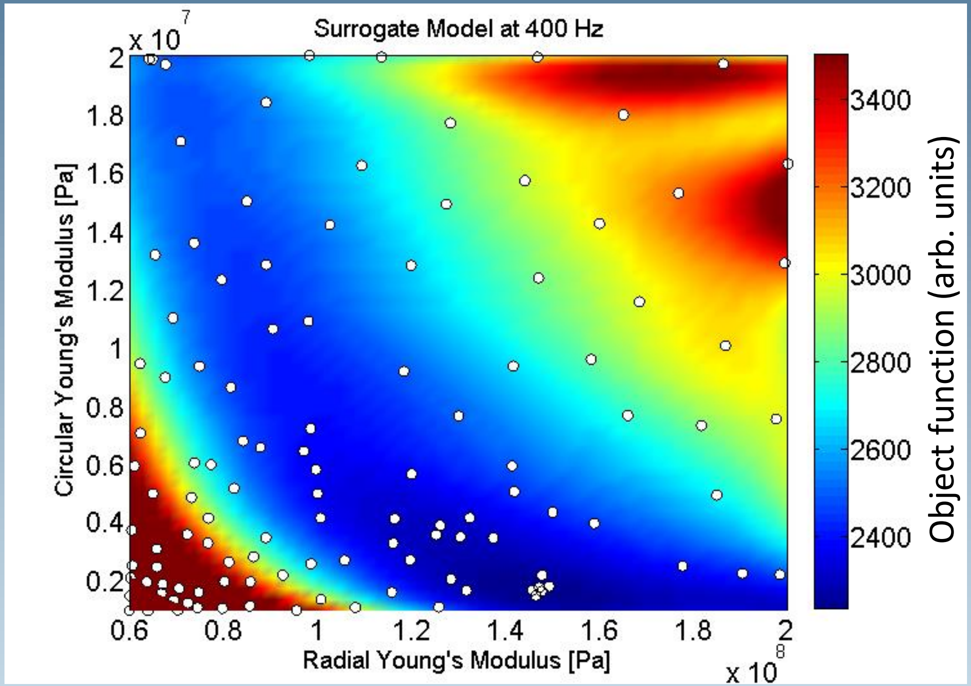
Experiment
[µm/Pa]
Model
[µm/Pa]
Displacement Amplitude
Experiment
[cycles]
Model
[cycles]
Displacement Phase

Holography

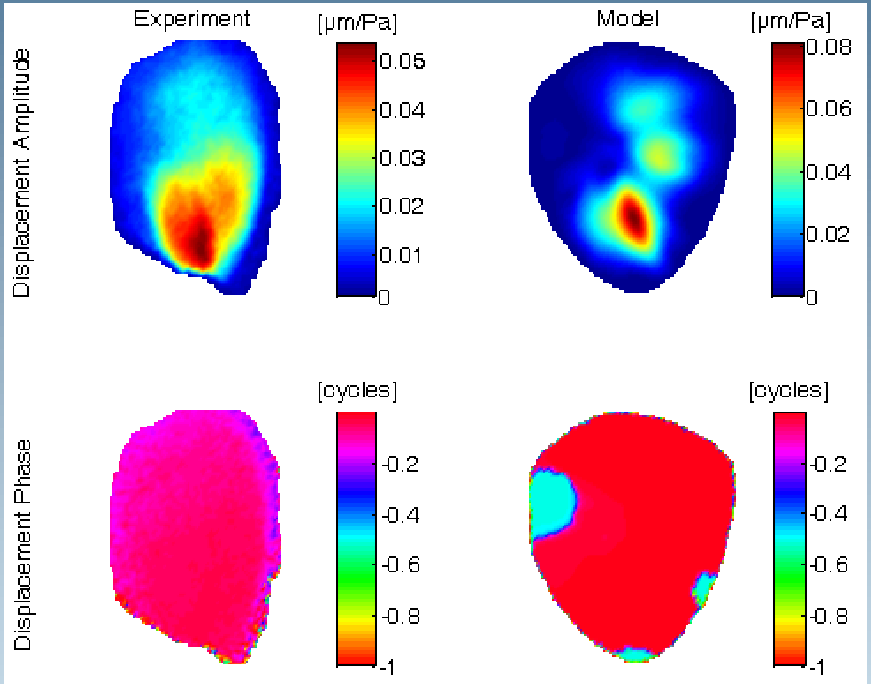
- 1600 Hz
  - $[E_{TM}, E_{EC}]$ = [40.3, 39.6] MPa
- 400 Hz
  - $[E_r, E_\theta]$ = [146, 1.52] MPa



Results



Surrogate Model at 400 Hz
x 10^7
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
Circular Young's Modulus [Pa]
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Radial Young's Modulus [Pa]
x 10^8
3400
3200
3000
2800
2600
2400
Object function (arb. units)



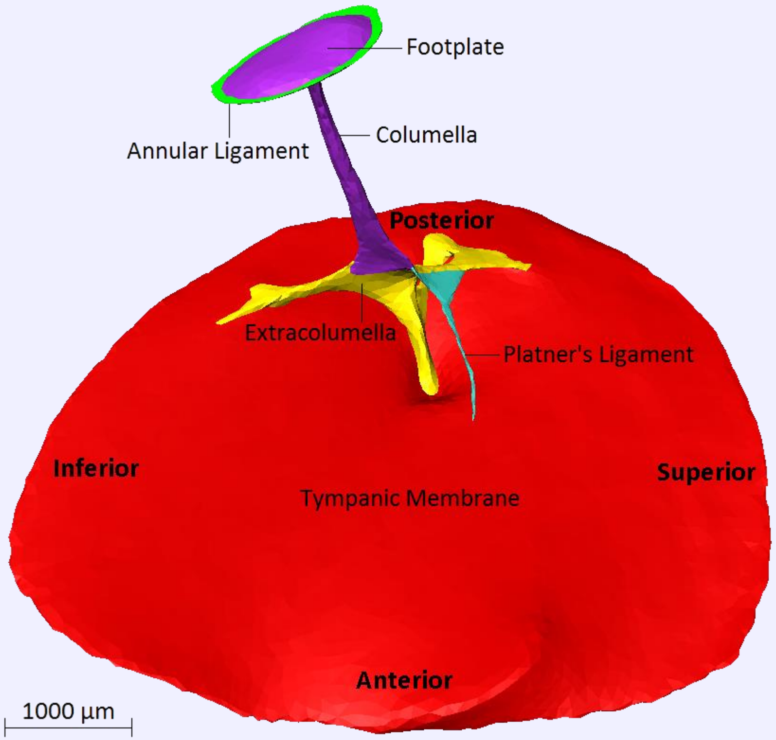
Experiment
Model
[µm/Pa]
0.05
0.04
0.03
0.02
0.01
0
0.08
0.06
0.04
0.02
Displacement Amplitude
Displacement Phase
[cycles]
-0.2
-0.4
-0.6
-0.8
-1

Holography

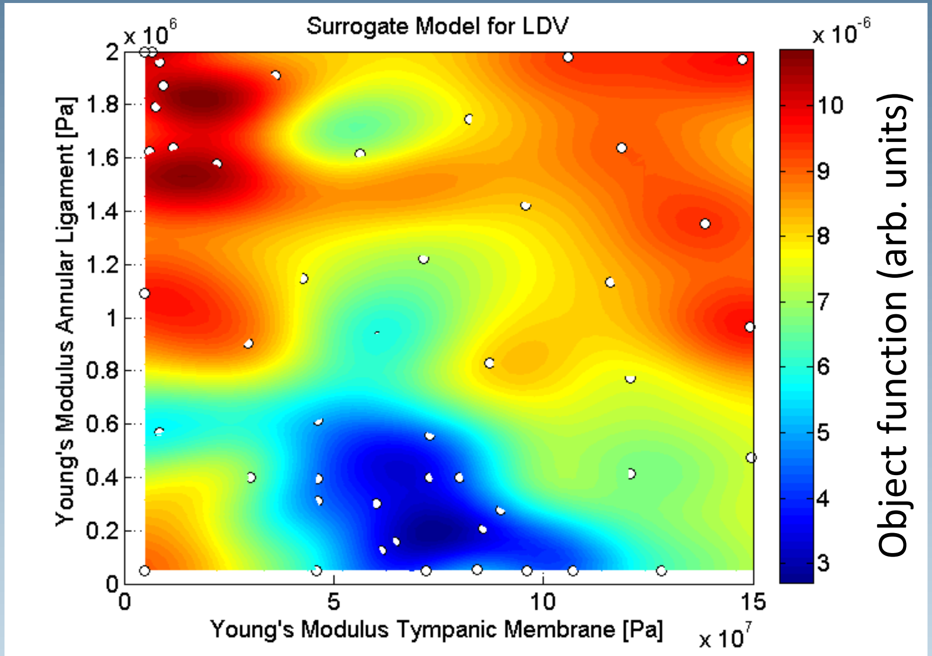
- 1600 Hz
  - $[E_{TM}, E_{EC}]$ = [40.3, 39.6] MPa
- 400 Hz
  - $[E_r, E_\theta]$ = [146, 1.52] MPa

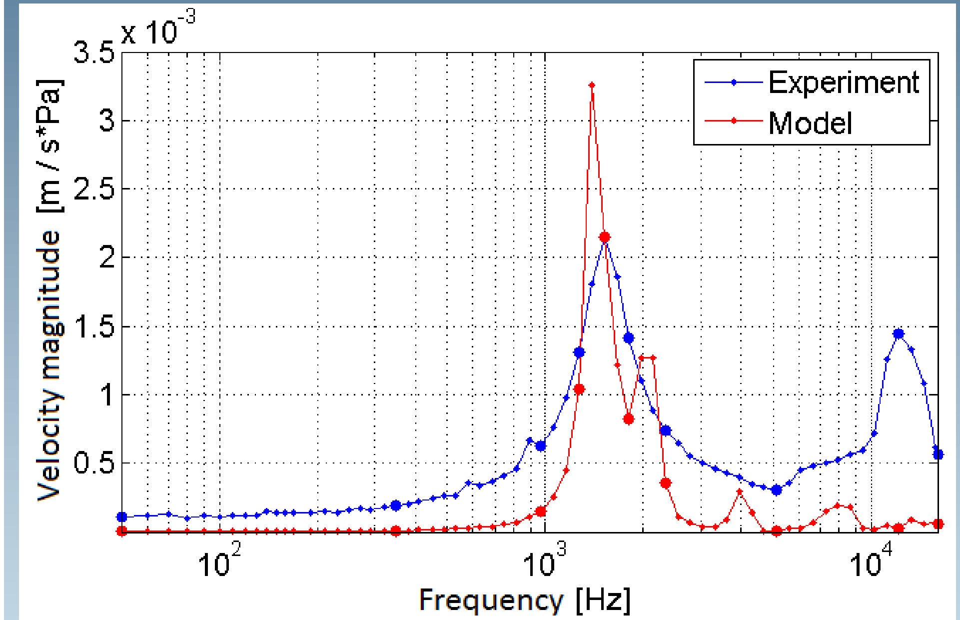
Vibrometry

- Multiple frequencies
  - $[E_{TM}, E_{AL}]$ = [64.5, 0.156] MPa



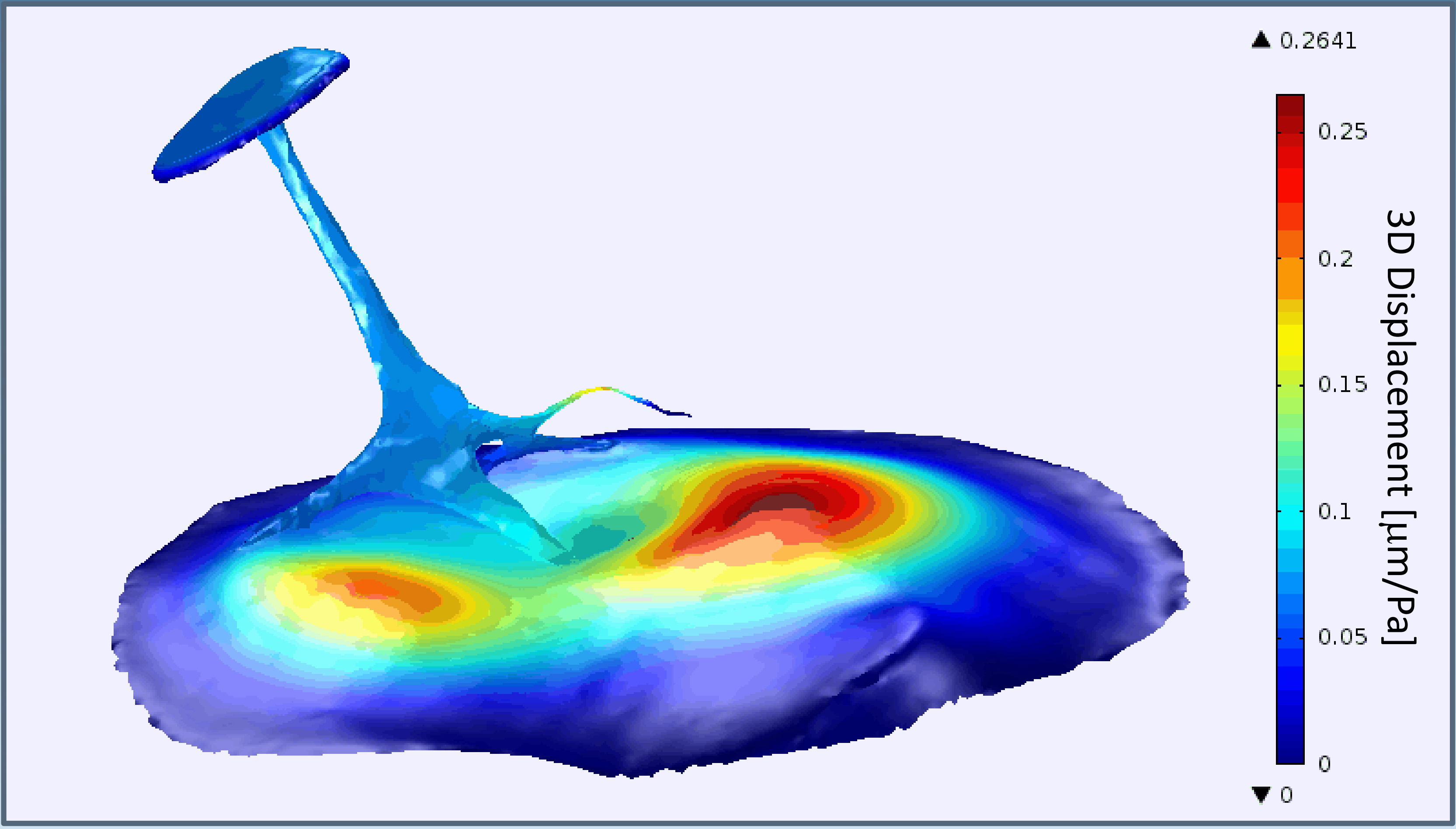
Results


Surrogate Model for LDV
x 10^6
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Young's Modulus Annular Ligament [Pa]
0
5
10
15
Young's Modulus Tympanic Membrane [Pa]
x 10^7
x 10^-6
10
9
8
7
6
5
4
3
Object function (arb. units)


x 10^-3
3.5
3
2.5
2
1.5
1
0.5
Velocity magnitude [m / s*Pa]
Experiment
Model
10^2
10^3
10^4
Frequency [Hz]

Results

1000 Hz



Conclusions & future

- Conclusions
  - Young’s modulus: most influential
  - Eardrum: radial ↔ circumferential elasticity
  - Footplate motion: translation + rotation
- Future
  - Compare different species
  - Improve meshing
  - Model prestrain
  - Optimize damping, etc.
  - Acoustic-shell interaction
  - Sensitivity & uncertainty
  - ...

Be like a duck. Calm on the surface,
but always paddling like the dickens underneath.

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Michael Caine


Antwerp by night
Thank you!


Antwerp by night
Thank you!