COMSOL CONFERENCE
2014 CAMBRIDGE

Acoustically Fluid-Structure Interaction Simulation of Differential Phase Sensor

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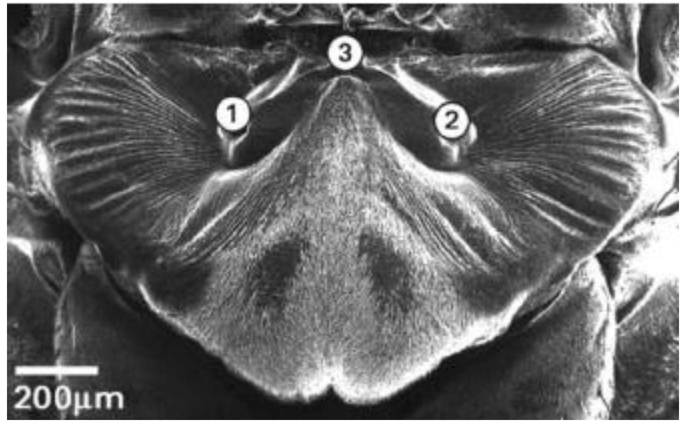
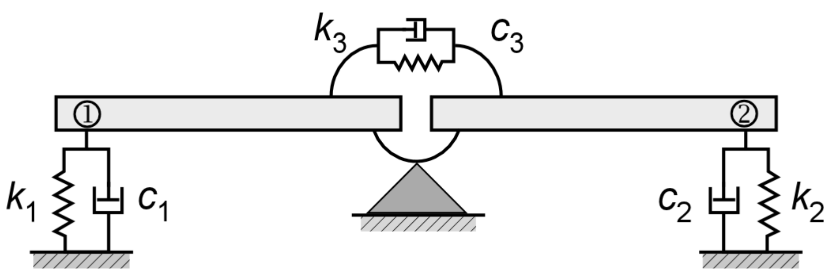
Outline

- Introduction
- Acoustically fluid-structure interaction
  - ✓ Fluid loading effect
  - ✓ Acoustic radiation damping
  - ✓ Verification of Lumped parameter model vs. FEA (Finite Element Analysis) model
- Results
- Conclusion
- Q & A

Introduction



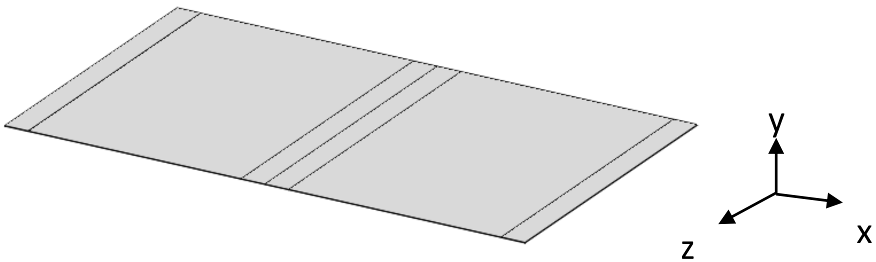
Hearing system of the fly, Ormia ochracea [1]



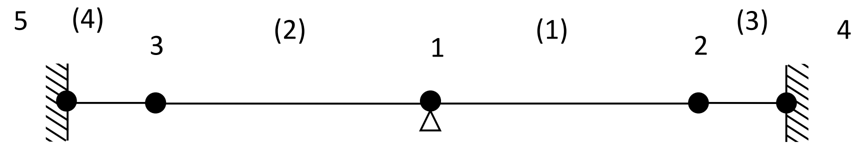
The Idealization of a hearing system of the fly, Ormia ochracea

[1] Miles, R. N., and et al., Mechanically coupled ears for directional hearing in the parasitoid fly Ormia ochracea, *J. Acoust. Soc. Am.*, **98(6)**, 3059-70 (1995)

2-D Sensor (Plane strain)



Three dimensional Finite Element Model with axes



Representation of the sensor composed of four beam elements where numbers and numbers with parenthesis represent nodes and elements

(a) (b)

(a) First (rocking) and (b) second (bending) eigenmode shapes of the hydro-acoustic sensor

FSI Problem in Frequency Domain

Acoustic Domain

Acoustics Module: Pressure Acoustics (acpr)

Wave equation

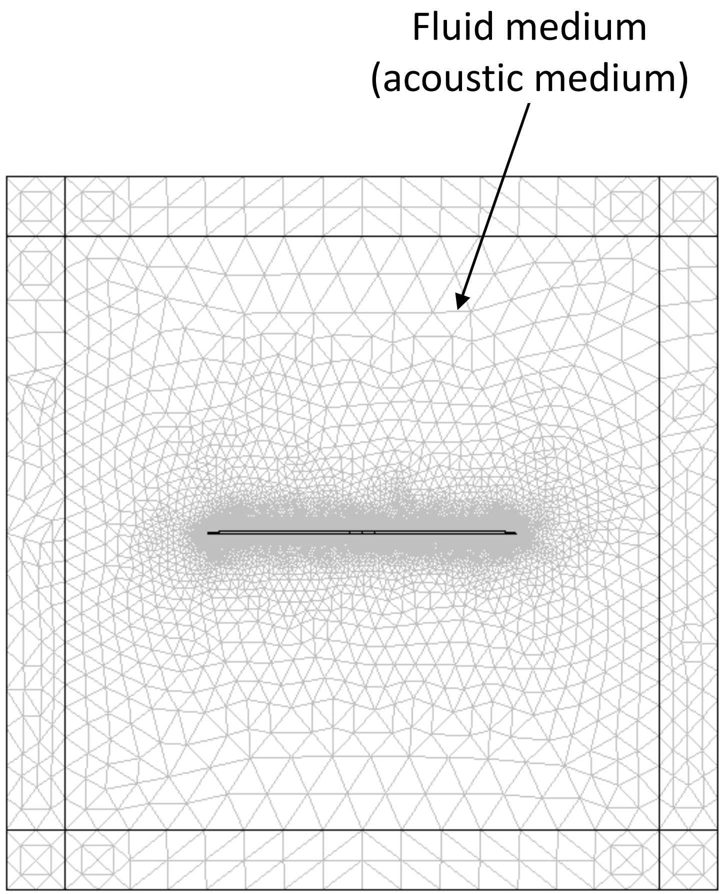
$$\frac{1}{\rho_0 c_s^2}\frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho_0}(\nabla p - q) \right) = Q$$

For a time-harmonic wave

$$p(x,t) = p(x)e^{i\omega t}$$

Helmholtz equation

$$\nabla \cdot \left(-\frac{1}{\rho_0}(\nabla p - q) \right) - \frac{\omega^2 p}{\rho_0 c_s^2} = Q$$



FSI Problem in Frequency Domain

Boundary & Interface Conditions

Acoustics Module: Pressure Acoustics (acpr) + Structural Mechanics Module: Plane Strain (acpn)

- *Infinite boundary* (*absorb boundary*):

  PML

- *Fluid-structure interaction* (FSI) *boundary:*

  To couple the acoustic pressure wave to the sensor,

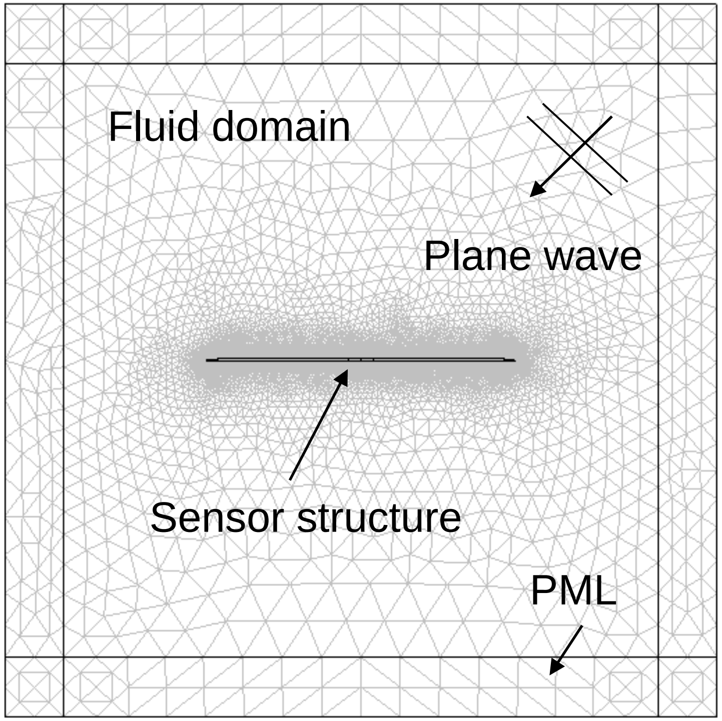
$$F = -n_s \cdot P$$

  To couple the sensor back to the acoustic problem,

$$-n \cdot \left(-\frac{1}{\rho_0} (\nabla p - q) \right) = a_n$$

  The equation for the interaction bet'n them

$$\{n\} \cdot \{\nabla P\} = -\rho_0 \cdot \{n\} \cdot \frac{\partial^2 U}{\partial t^2}$$



FSI Problem in Frequency Domain

Solid Domain

Structural Mechanics Module: Plane Strain (acpn)

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix}$$

Constitutive law $\sigma = D\varepsilon$

where

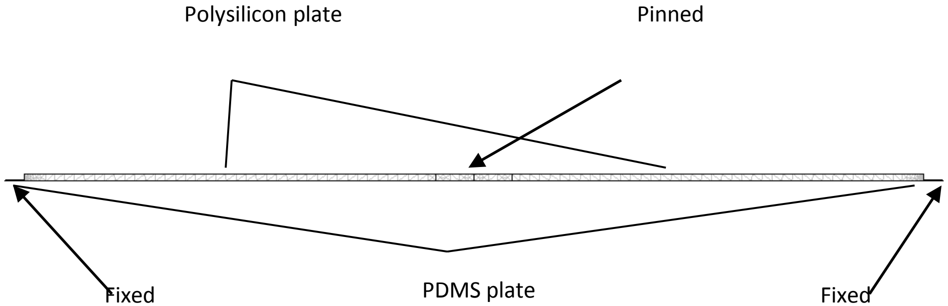
$$D = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix}$$

Equilibrium equations

$$-\frac{\partial \sigma_x}{\partial x} - \frac{\partial \tau_{yz}}{\partial y} = F_x$$

$$-\frac{\partial \tau_{xy}}{\partial x} - \frac{\partial \sigma_y}{\partial y} = F_y$$

$$\sigma_{yx} = \sigma_{xy}$$

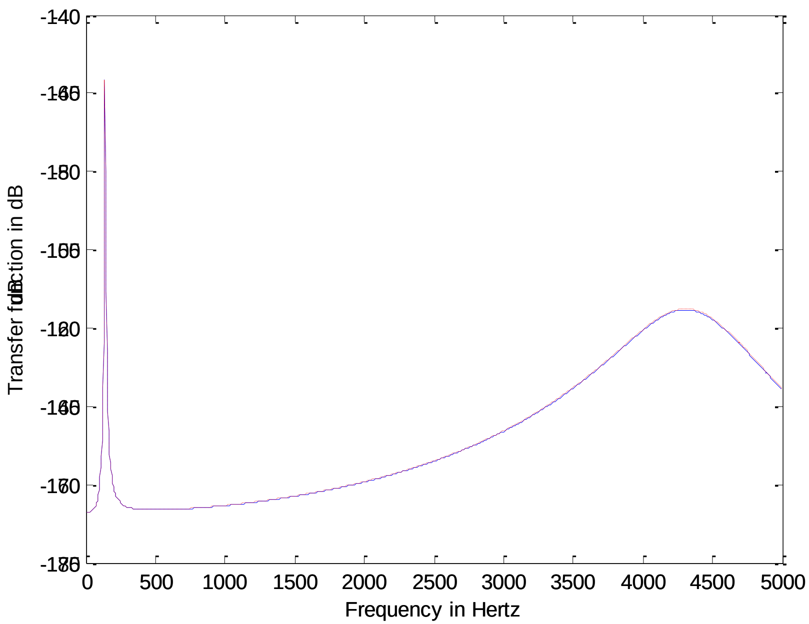


Sensor model with material and boundary conditions

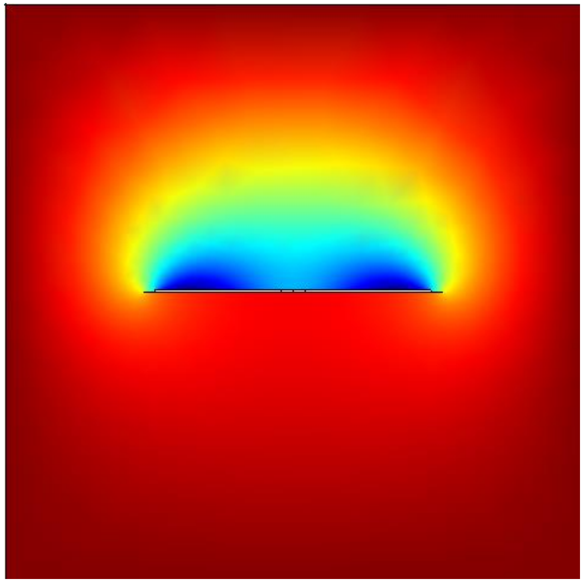
Acoustic Radiation Damping

$$\mathbf{C_F} = \alpha_{dM}\,\mathbf{M_F} + \beta_{dK}\,\mathbf{K_F}$$

Rayleigh (proportional) damping



Frequency response of the sensor in water.

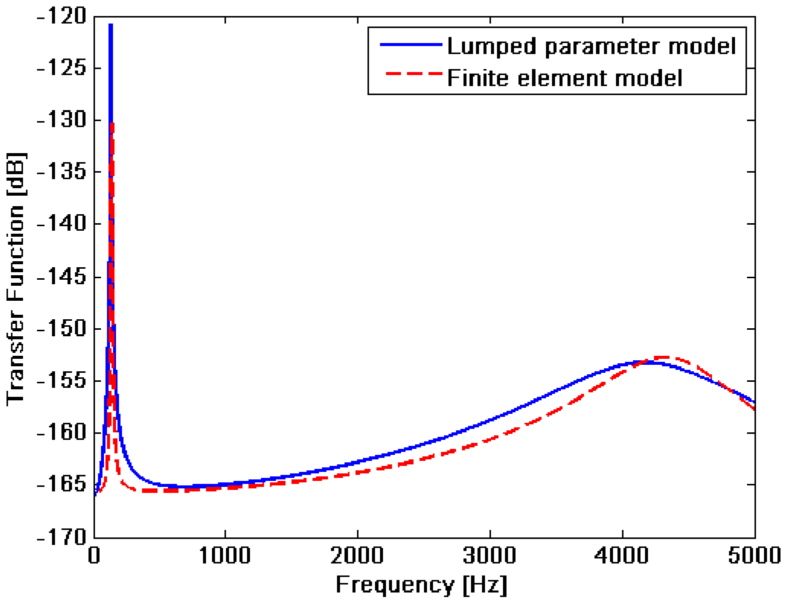


Post processing plot of the total acoustic pressure at 5000 Hz

Results: Fluid loaded mass & Acoustic Radiation Damping

Natural frequencies	1st natural frequency	2nd natural frequency
In vacuo	870 Hz	18469 Hz
In water	137 Hz	4300 Hz
Percentage decrease	84 %	74 %

Table : Comparison for *in vacuo* and in water natural frequencies of the hydro-sensor



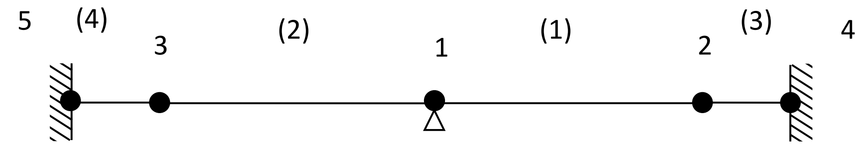
Comparison of frequency responses by FE and lumped parameter models for a sensor in water.

Results: Validation of Lumped-Parameter Model

Galerkin's method of Beam formulation

$$\mathbf{M}_{\mathbf{F}}\ddot{\mathbf{u}}_{\mathbf{F}} + \mathbf{C}_{\mathbf{F}}\dot{\mathbf{u}}_{\mathbf{F}} + \mathbf{K}_{\mathbf{F}}\mathbf{u}_{\mathbf{F}} = \mathbf{f}_{\mathbf{F}}$$

where
$$\begin{cases} f_1 = s p_o e^{i\omega\tau/2} \\ f_2 = s p_o e^{-i\omega\tau/2} \end{cases}$$



Representation of the sensor

Transfer functions

$$\begin{cases} TF_1(\omega) = \dfrac{\det\left(\mathbf{K} - \mathbf{M}\omega^2\big|_{(,2)=\mathbf{f}}\right)}{\det\left(\mathbf{K} - \mathbf{M}\omega^2\right)} \\ TF_2(\omega) = \dfrac{\det\left(\mathbf{K} - \mathbf{M}\omega^2\big|_{(,4)=\mathbf{f}}\right)}{\det\left(\mathbf{K} - \mathbf{M}\omega^2\right)} \end{cases}$$

where $\mathbf{A}\big|_{(,j)=\mathbf{f}}$ represents a matrix $\mathbf{A}$ with the *j*-th column replace by a vector $\mathbf{f}$

Conclusion

- Acoustically fluid-structure interaction has been performed which consists of an underwater sensor in fluid medium using COMSOL Multiphysics Module.

- Simulated results are used to validate the lumped parameter model of the sensor developed in [2].

- Simulated results are used to calculate sound radiation due to the vibration of the sensor in the fluid domain.

[2] Lee, J., *et al.*, Modeling and Characterization of Bio-Inspired Hydro-Acoustic Sensor, *Journal of Acoustics and Vibrations*

Thank you!