ETREMA Products, Inc.

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Linear Magnetostrictive Models in Comsol

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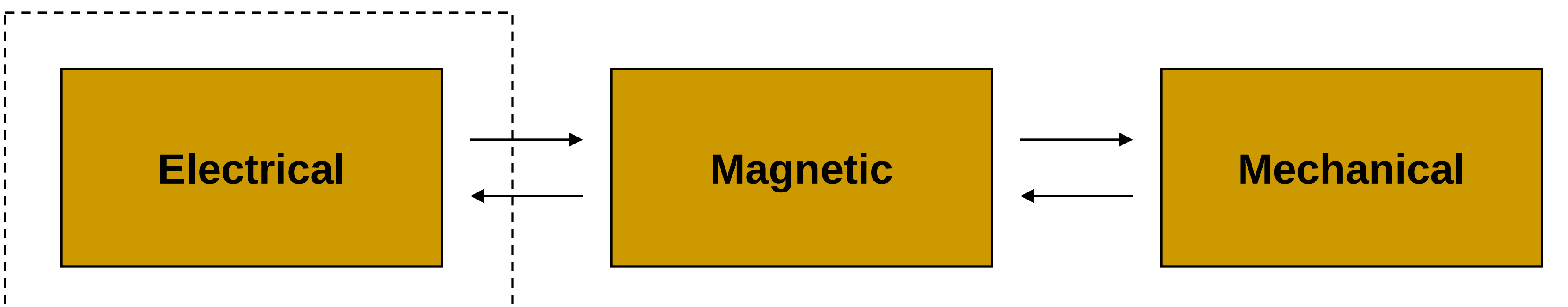
Overview

- Magnetostriction
- Equations
- Comsol models
- Examples
- Conclusions

Magnetostriction

- Coupling between magnetic and mechanical fields in a particular type of material
  - Mechanical response to a magnetic input
  - Magnetic response to a mechanical input
- Multi-physics coupling makes it ideal for modeling with Comsol



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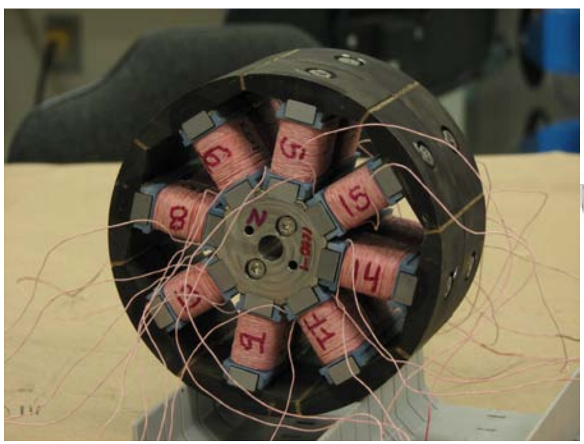
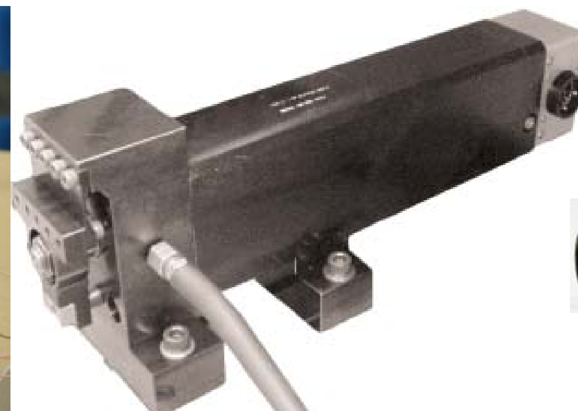
Uses of magnetostrictive materials

- Sonar, micro-positioning, ultrasonic processing, energy harvesting
- Typical transducers consist of magnets, coils, high flux materials, and mechanical interface
- Operated at a single frequency or across a broad frequency band

Origin of magnetostriction

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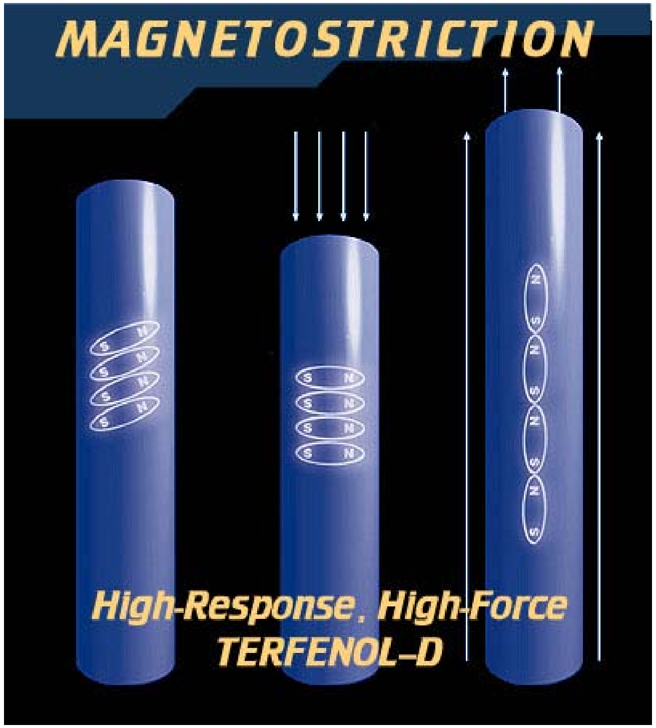
- Magnetostriction is coupling between the magnetic and mechanical domains in a material
  - Joule effect – change in shape of a material in response to a magnetic field
  - Villari effect – change in magnetic state of a material in response to an applied stress
- Magnetostriction is caused by magnetic domain wall motion and domain rotation
  - Magnetic domains are inherent to the material crystal structure
  - Several common materials exhibit magnetostriction including iron and nickel (on the order of 15-30 microstrain)
- Materials that exhibit extraordinary amounts of magnetostriction are referred to as “giant” magnetostrictive materials



Free state | Applied stress | Applied magnetic field

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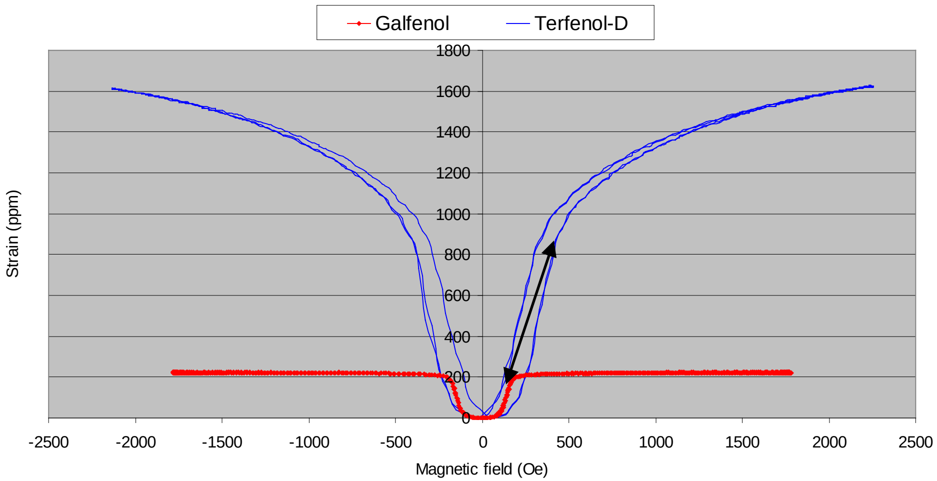
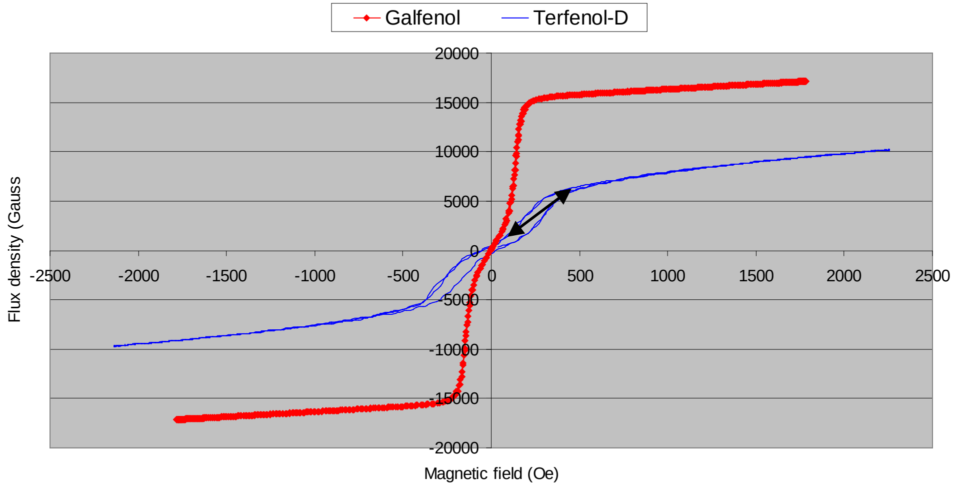
Giant magnetostrictive materials

- Terfenol-D (TbFeDy alloys)
  - Up to 2000 microstrain
  - Saturates at ~1500 Oe
  - Very high energy density
  - Brittle, crystalline material, must be used in compression
- Galfenol (FeGa alloys)
  - Up to 400 microstrain
  - Saturates at ~150 Oe
  - Not as high energy density as Terfenol-D
  - Structural material, machinable, weldable, can be used in tension
- Nonlinear behavior - typically operated with a magnetic bias and a relatively small AC field to get bi-directional motion





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Linear magnetostrictive equations

- Full 3D magnetostrictive equations

$$T = c^B S - h_t B$$

$$H = -hS + \gamma^S B$$

- T is stress, c^B is the compliance matrix with constant magnetic flux density, S is strain, h and h_t are magnetostrictive coupling coefficients, H is magnetic field, B is flux density, and γ^S is the inverse of permeability

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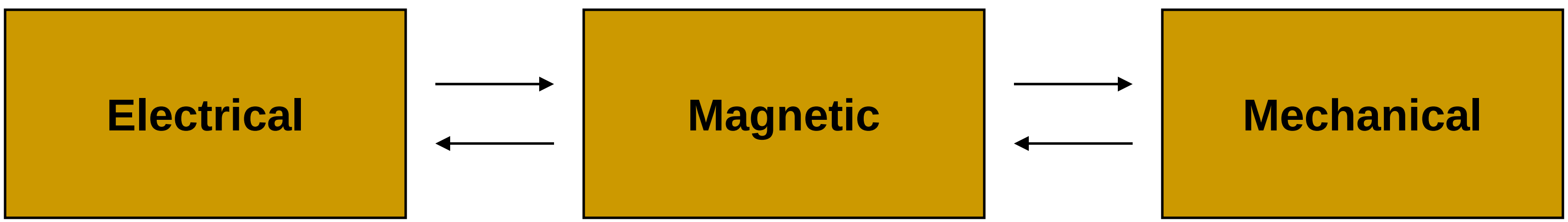
Model Setup

- Joule effect
  - Electrical input – voltage or current into a coil
  - Magnetic fields are generated
  - Magnetostrictive material strains (displaces)



- Villari effect
  - Mechanical input (stress or strain) to the magnetostrictive material
  - Magnetic fields are generated
  - Electric fields are generated in a coil

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Use of Comsol

- Comsol modules
  - Structural mechanics module – alternatively Acoustics or MEMS could be used
  - AC/DC module
- Magnetostrictive model was implemented by modifying the stress and magnetic field variables
  - $-h_t B$ in the stress variables
  - $-hS$ in the magnetic field variables
- Electrical impedance can be calculated using input voltage or current and the induced electric fields in the coil (measure of the transducer behavior)

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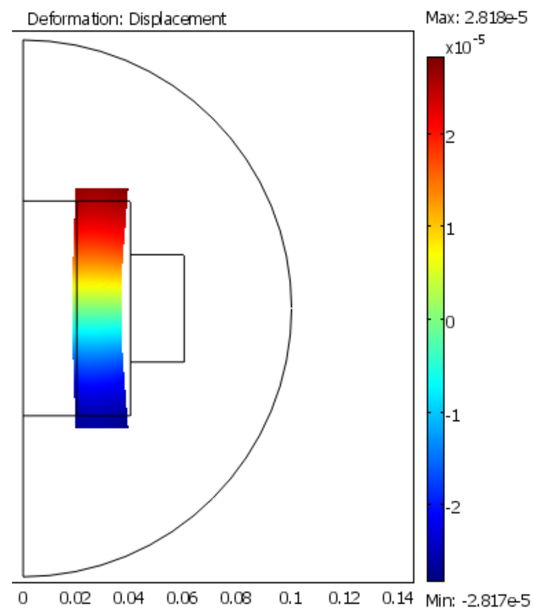
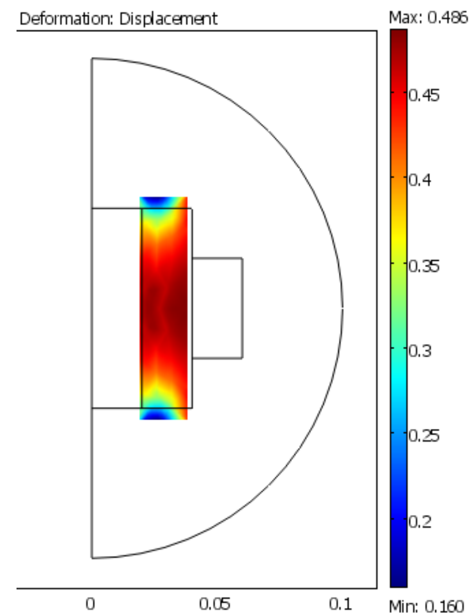
Simple 2D model

- Simple model of material, air, and coil
- Used to verify Joule effect and Villari effect
- Shows expected magnitude of response



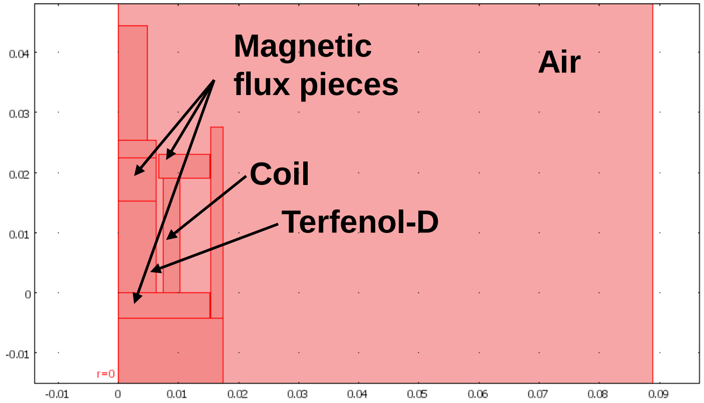
Joule effect

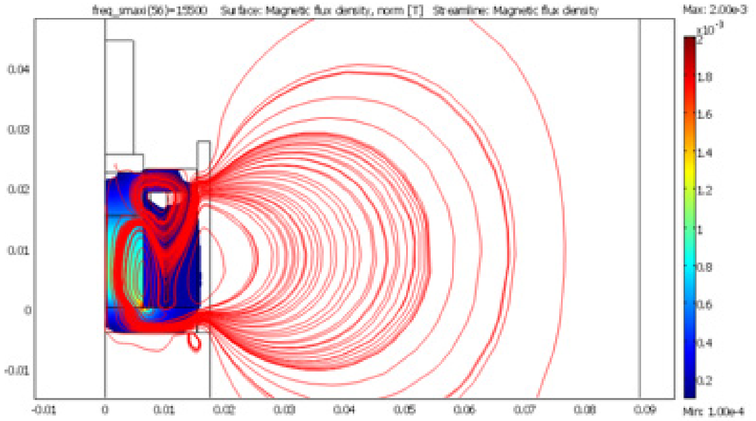


Villari effect

2D axisymmetric model of a transducer

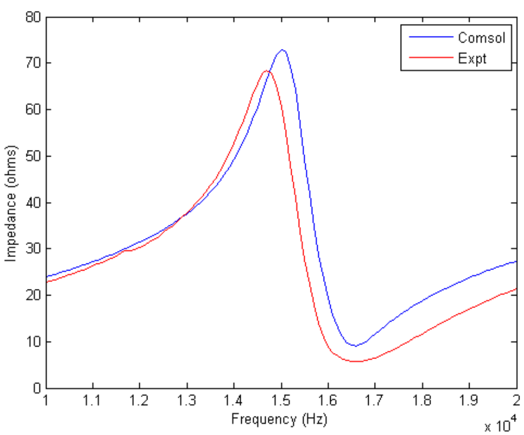
- An existing Terfenol-D transducer was modeled with a 2D axisymmetric representation and a 1V input to the coil
- A harmonic solution from 10-20 kHz was performed in order to capture the resonance around 15.5 kHz

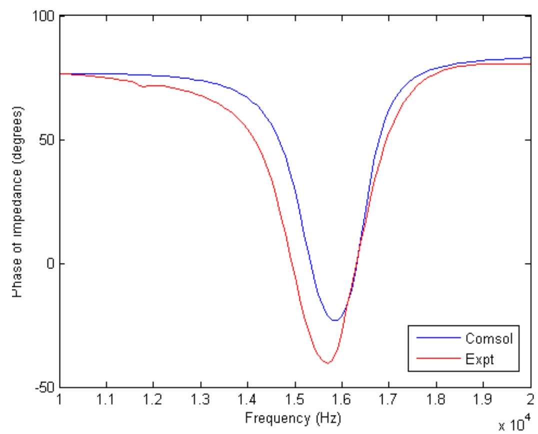


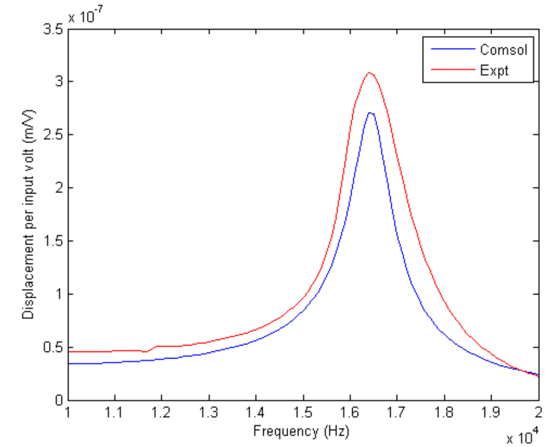


Impedance and displacement results

- Comparisons of experimental data and Comsol results show very good agreement
- Impedance and phase are very similar
- Magnitude of displacement is close







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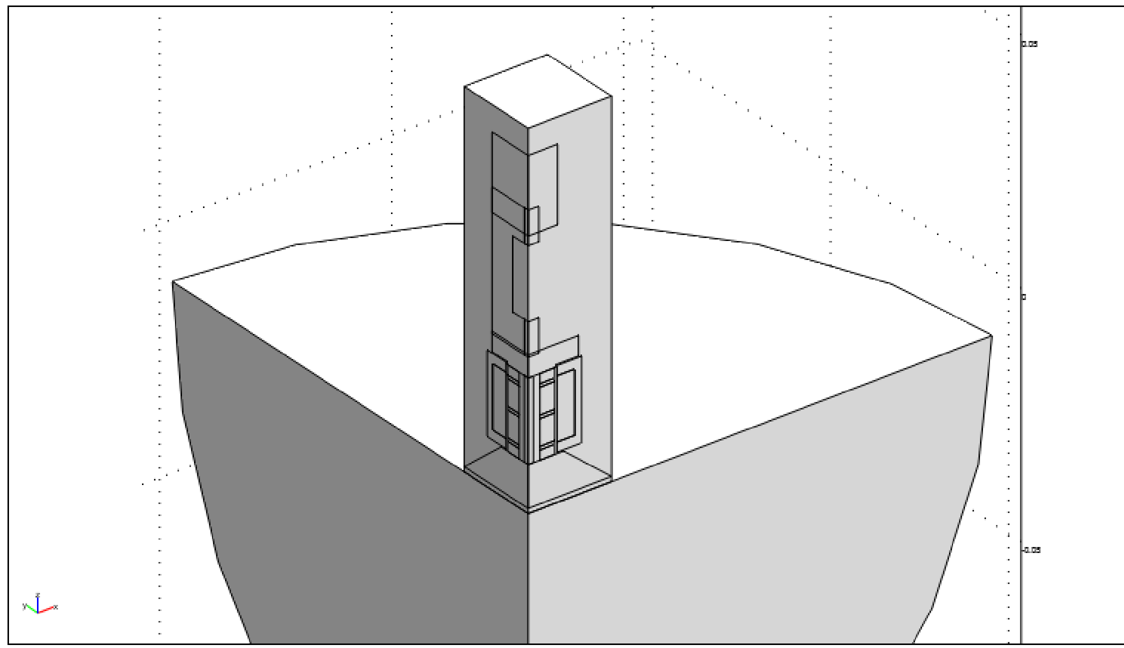
3D models

- Terfenol-D and Galfenol in the same transducer
- Not axisymmetric – 3D is necessary for modeling
- Includes a water load on the transducer face



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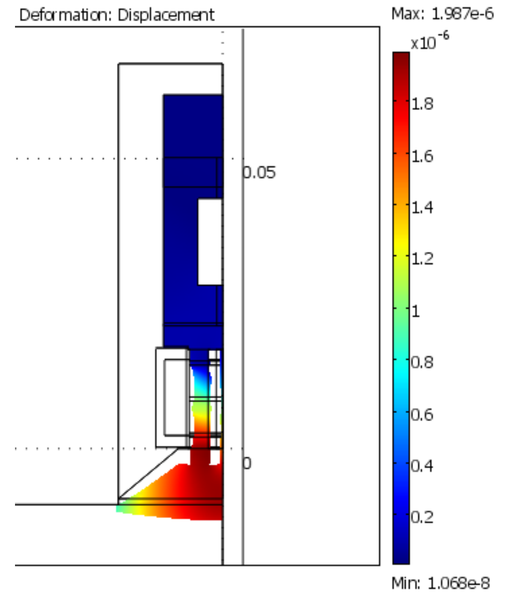
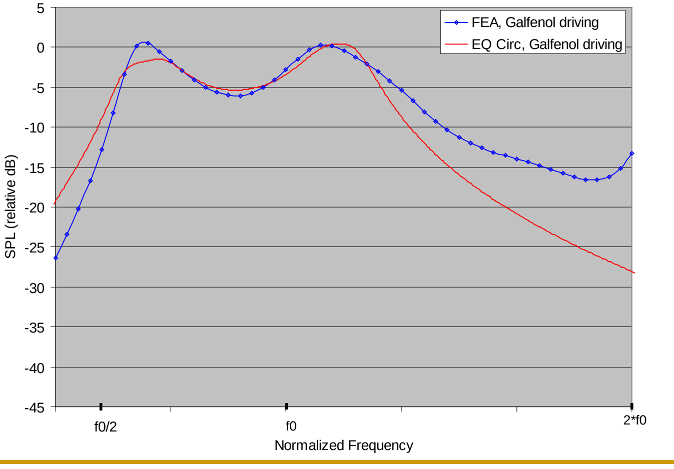
Results of 3D model

- Driving only the lower (Terfenol-D) section
- Acoustic source level calculations match equivalent circuit predictions
  - Equivalent circuit models are a 1D model and do not capture complicated motion of the head mass
  - Displacement show that the head mass is starting to “flap” which affects the high frequency output





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Conclusions and Future Work

- Models do a very good job of capturing behavior of magnetostrictive transducers
- 2D and 3D models are working fine and have reasonable solution times (a few minutes for 2D, 1-2 hours for 3D)
- Future work will focus on
  - Calculating impedance for 3D models
  - Validating more results against test data
  - Expanding to nonlinear material behavior