COMSOL CONFERENCE BOSTON 2013

The Use of Multiphysics Models in the Design and Simulation of Magnetostrictive Transducers

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ETREMA Products, Inc.

Designer and manufacturer of technology driven, high value systems based on electromagnetics.

- Small business
- Started in 1990 as a foundry for TERFENOL-D
- Developed engineering capability in the 90's to grow the market
- Shifted to system approach in 2000's

Today's Talk

- What is magnetostriction?
- Magnetostrictive devices
- Modeling magnetostriction
  - Tools & how they are used
- Three examples of using COMSOL in various phases of a product development
  - Design example
  - Validation of modeling tools
  - Diagnosis of a design flaw
- Future modeling efforts
- Summary

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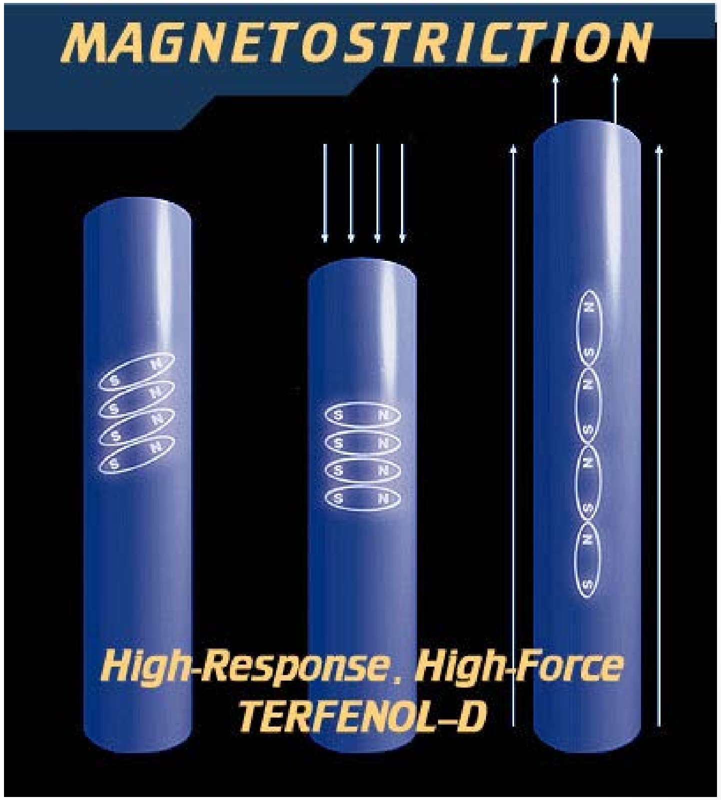
What is magnetostriction?

- Inherent property of ferromagnetic materials where the magnetic and mechanical domains are coupled
  - Applied magnetic field results in a change in the mechanical state of the material (Joule)
  - Applied stress or strain results in a change in the magnetic state of the material (Villari)
- Magnetostrictive materials
  - Nickel, iron, transformer steels: strain <50 με
  - Iron-gallium alloys (Galfenol): strain 150-450 με
  - Rare earth-iron alloys (Terfenol-D): strain >1000 με



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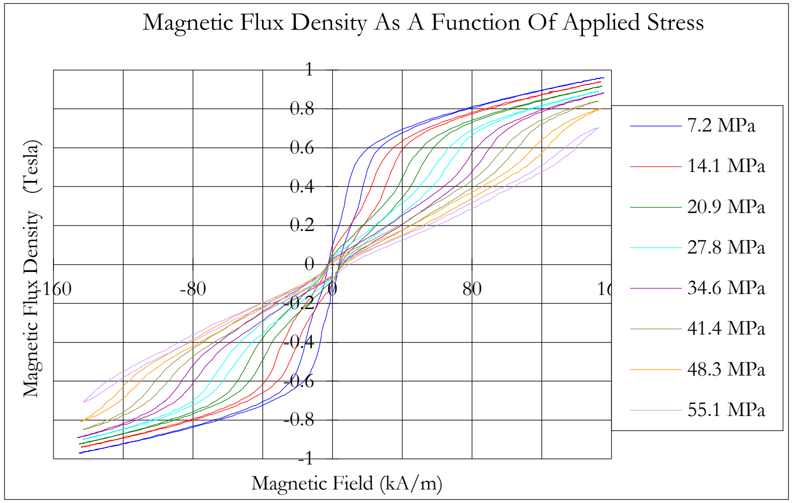
Characteristics of magnetostrictive materials

- Nonlinear material behavior
  - Material properties are not constant (Young's modulus, magnetic permeability)
  - Response is highly dependent on mechanical and magnetic states



Data for Terfenol-D produced by ETREMA

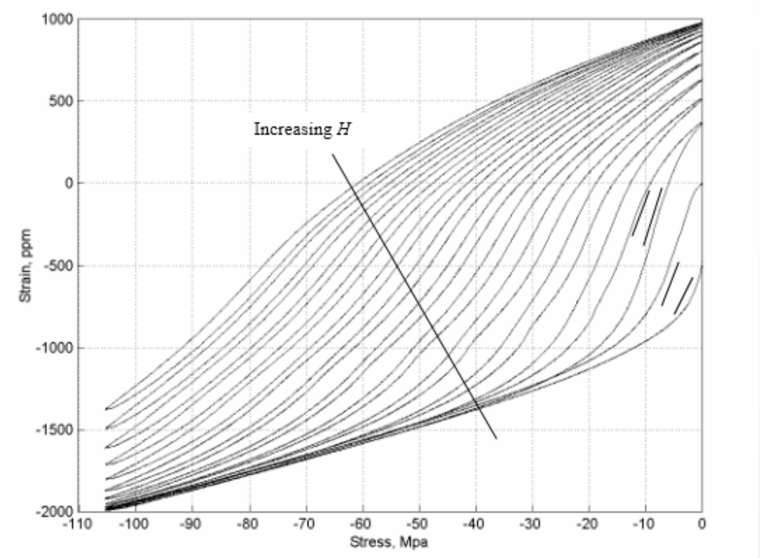


Figure from: R.A. Kellogg , *The Delta-E Effect in Terfenol-D and Its Application in a Tunable Mechanical Resonator*, M.S. Thesis, 2000. p. 45

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Linear magnetostrictive equations

$$S = s^H T + d_t H$$

$$B = dT + \mu^T H$$

Field Variable	Description
S	Strain (m/m)
T	Stress (Pa)
B	Magnetic flux density (Tesla)
H	Magnetic field (A/m)

Material property	Description
s^H	Compliance matrix at constant H
d, d_t	Magnetostrictive coefficients ($\delta B/\delta T$, $\delta S/\delta H$)
μ^T	Magnetic permeability at constant stress

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Magnetostrictive transducers

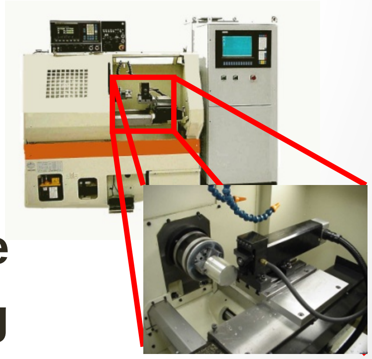
- Used in a wide array of applications and industries
- End application drives the device design

Navy Active SONAR

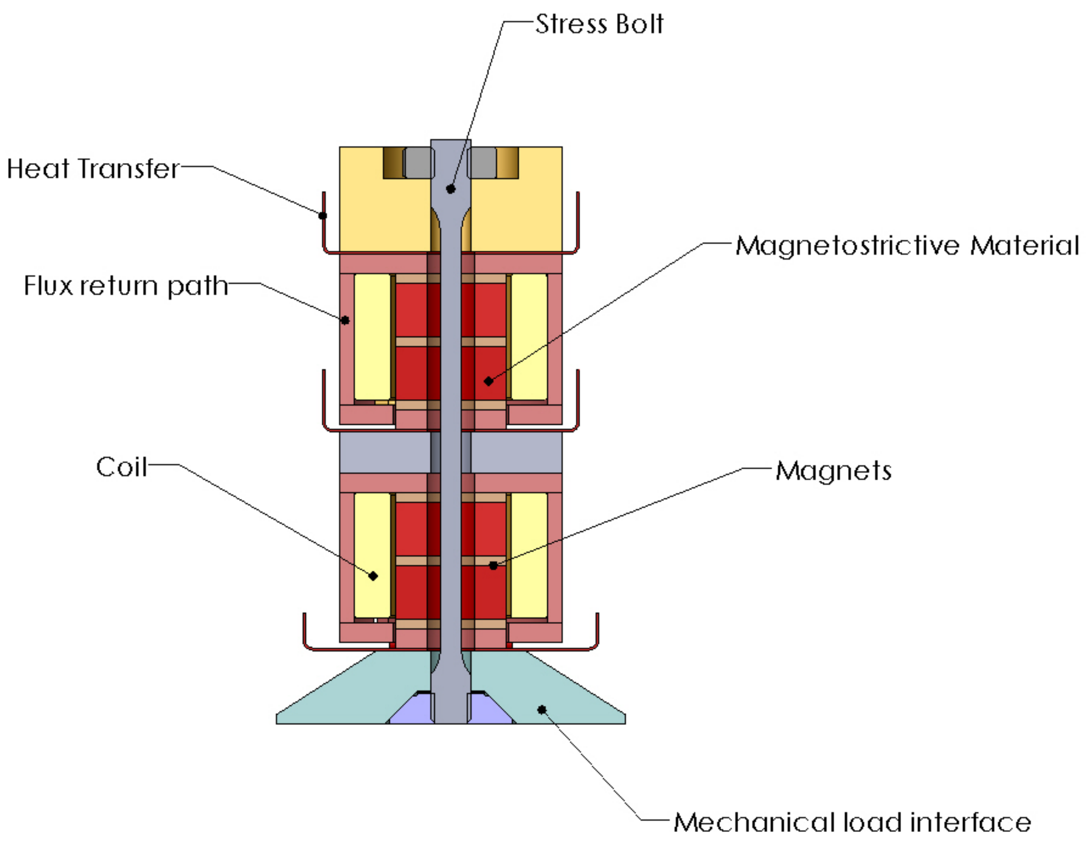
STARS – Law enforcement

Standard actuators – DC to 25 kHz

AMS – Small Engine Piston Turning



What is in a transducer?



- Magnetostrictive material
- Permanent magnets
- Coil
- Magnetic flux carrying components
- Structural components
- Thermal transfer components

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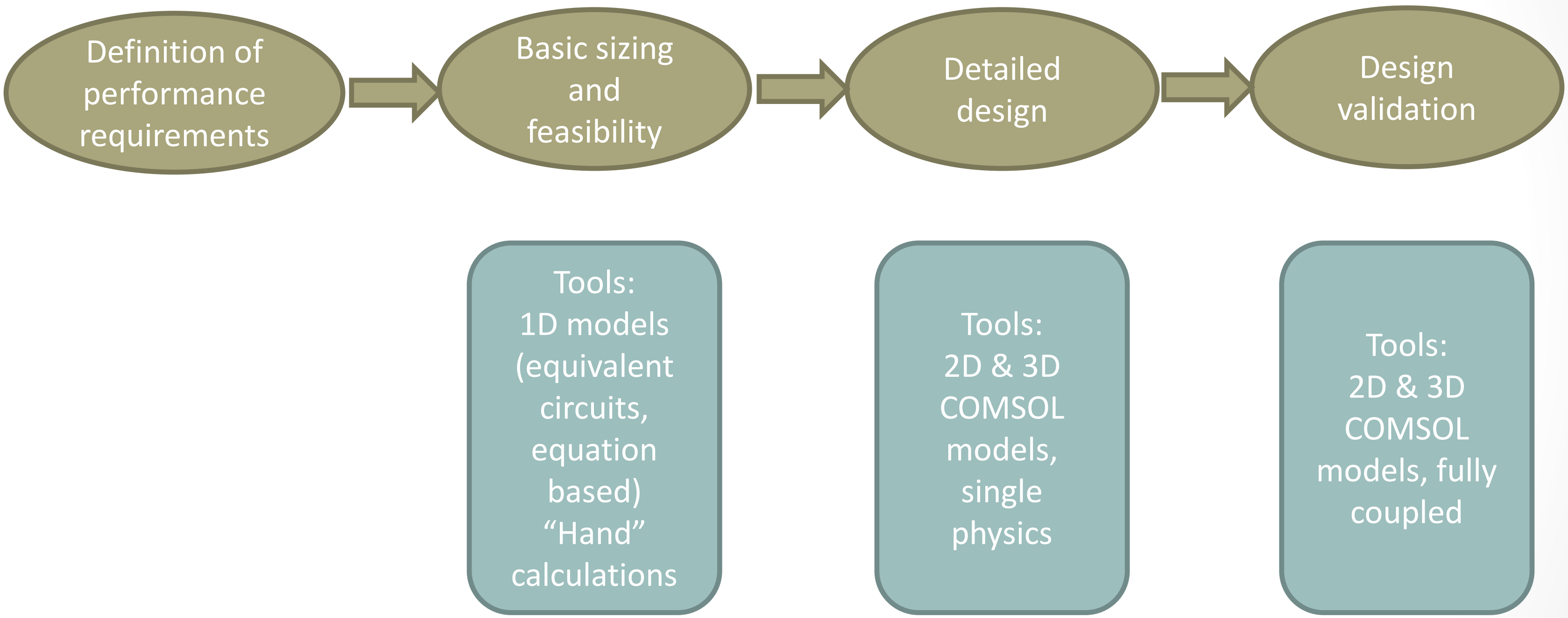
Transducer design process



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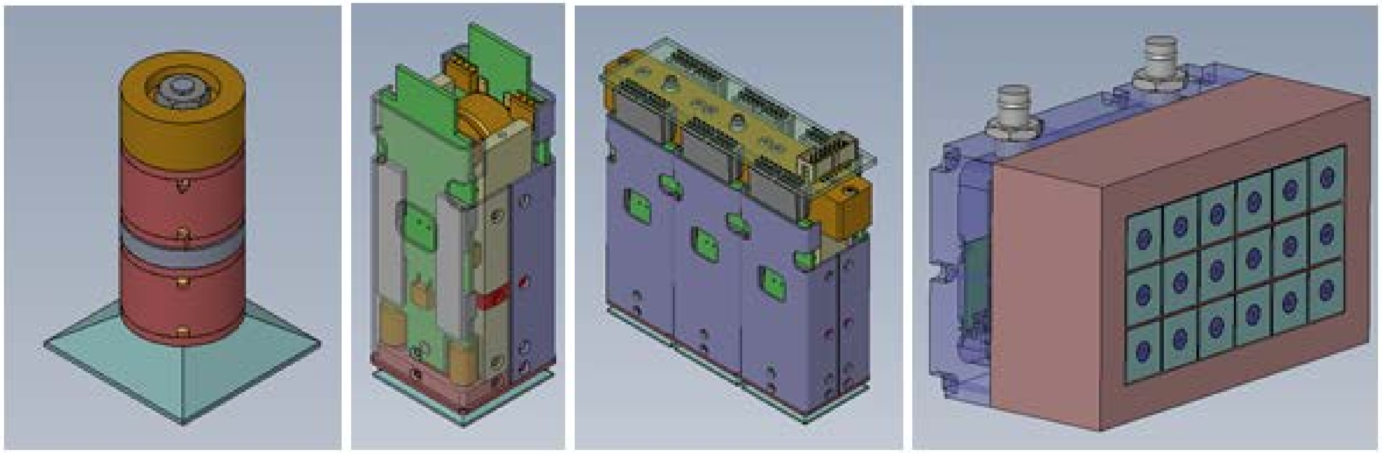
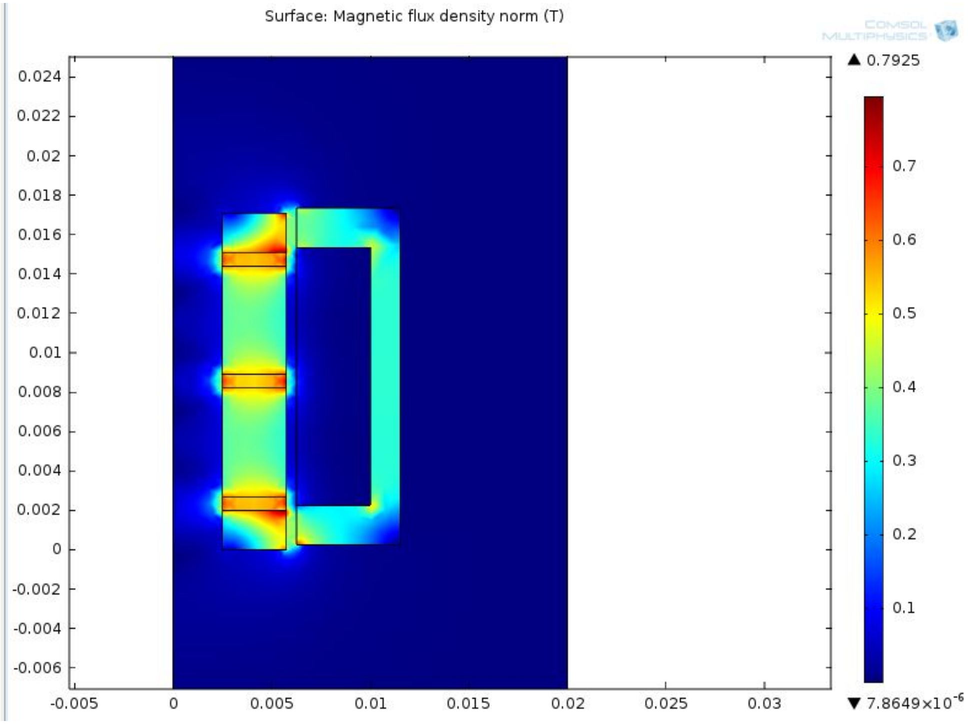
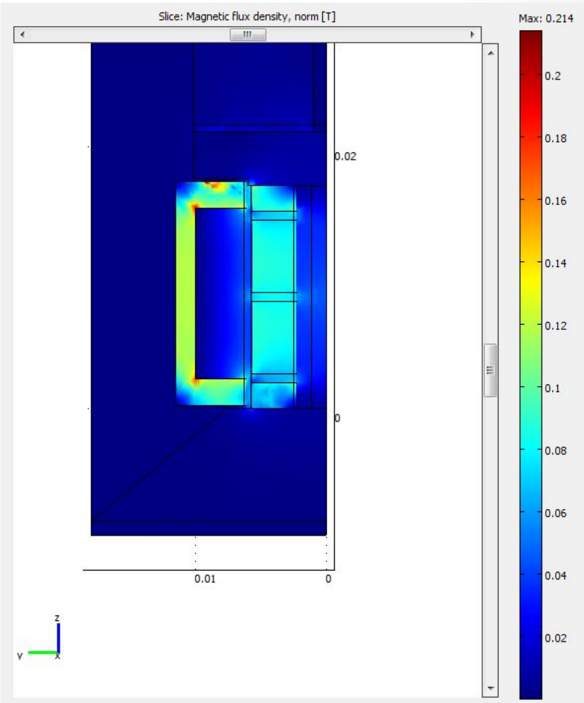
Design example

- Small SONAR source
  - Broad bandwidth
  - High SPL
  - Compact
- The intent is to package it with integrated electronics
  - Stray magnetic flux can interfere with electronics
  - Heating/cooling of both the transducer and electronics is a concern
- Eventual use is in a close-packed array



Magnetic models





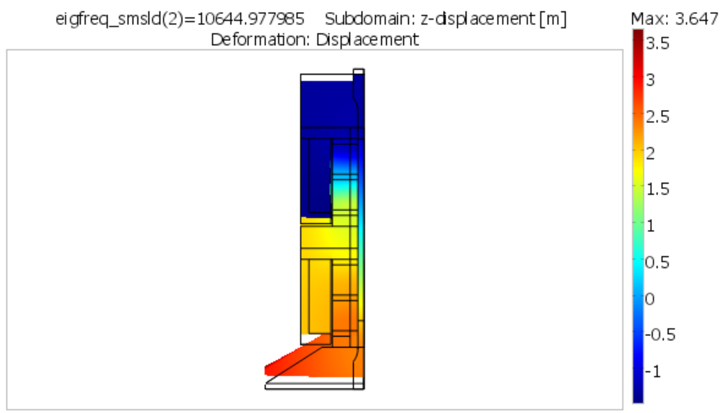
<u>DC magnetics</u>

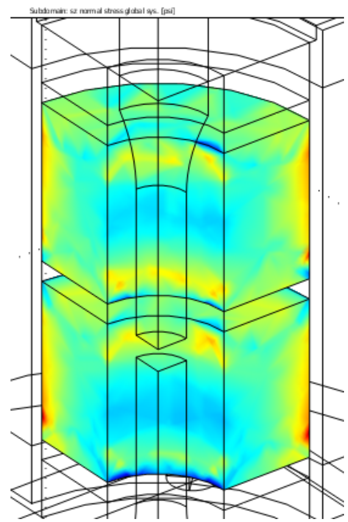
- Size permanent magnets to appropriately bias the material at the design prestress
- Size additional magnetic circuit components to carry the magnetic flux - avoid saturation

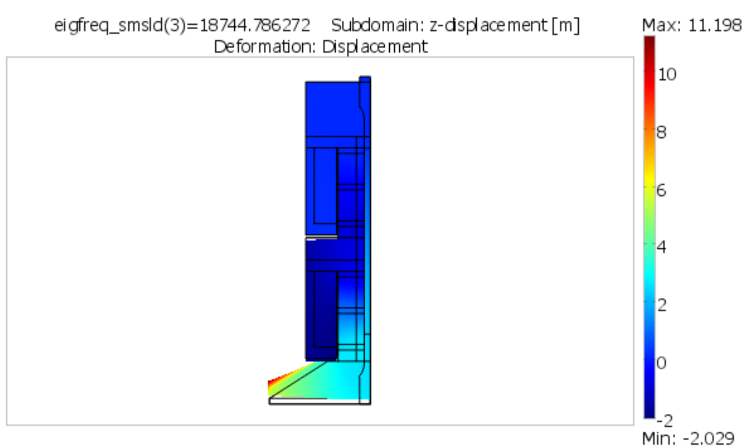
<u>AC magnetics</u>

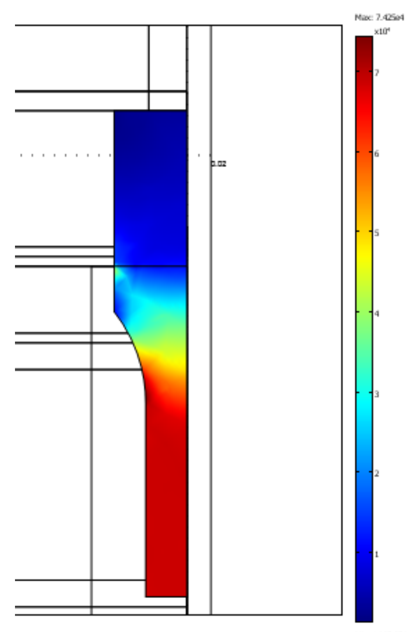
- Size the coil and other components to generate the alternating magnetic fields needed to produce the appropriate mechanical output
- Match the transducer electrical requirements with available power amplifiers
- Evaluate losses due to eddy currents

Mechanical models

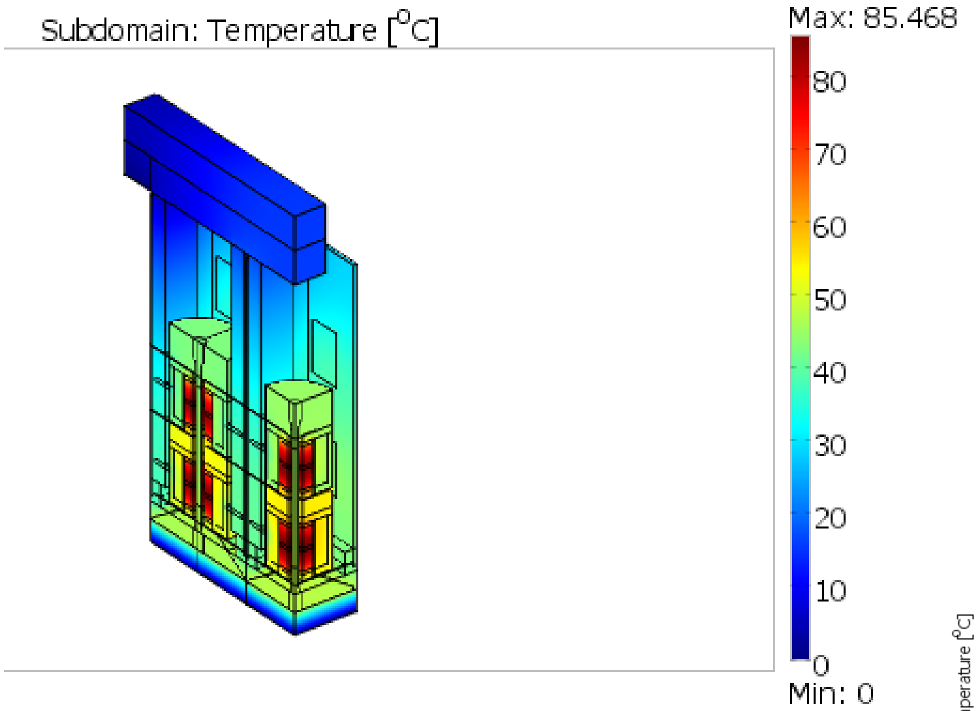


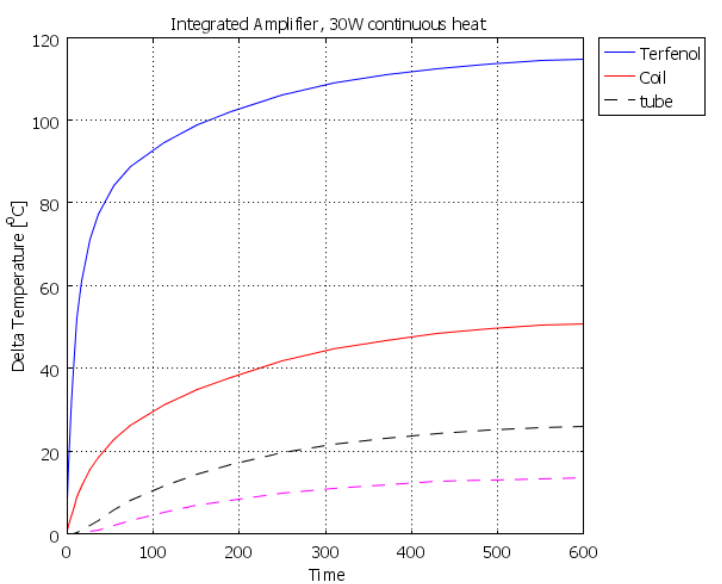






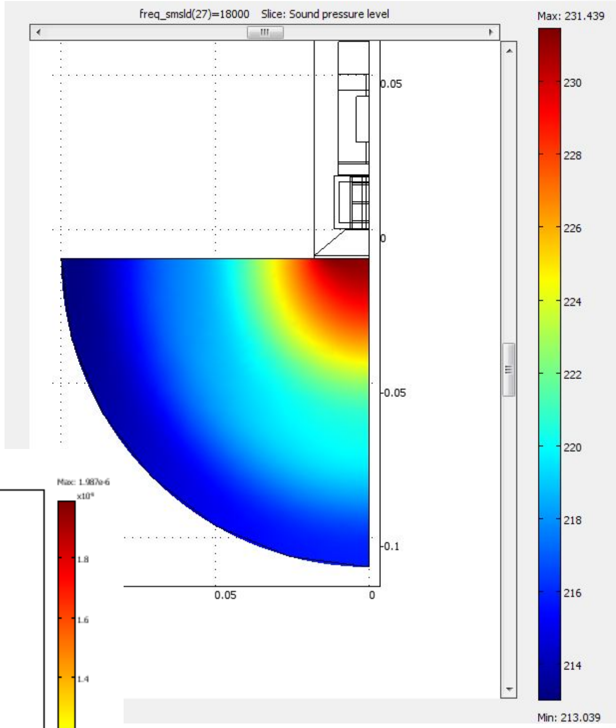
Thermal models

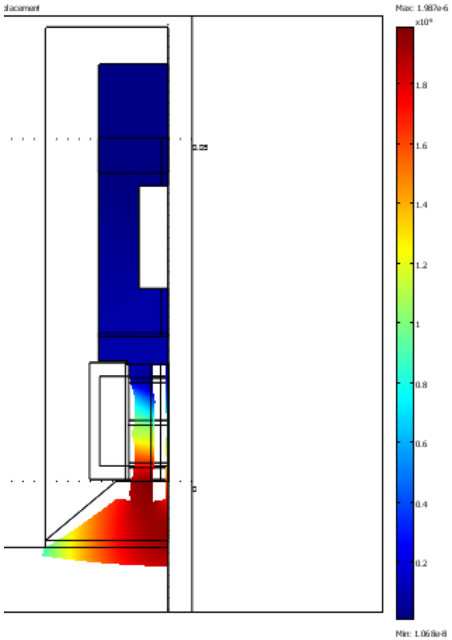




Magnetostrictive FEA models

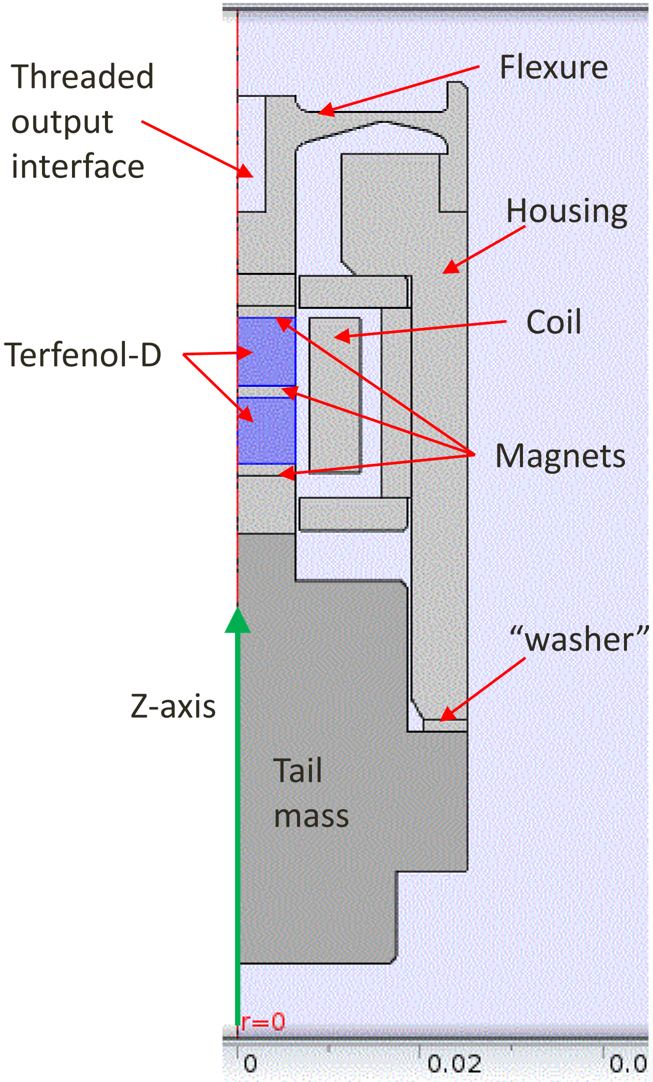
- Coupled linear magnetostrictive model
  - Assumes a magnetically biased design
  - Small signal analysis
- Coupled to a water load to calculate acoustic output



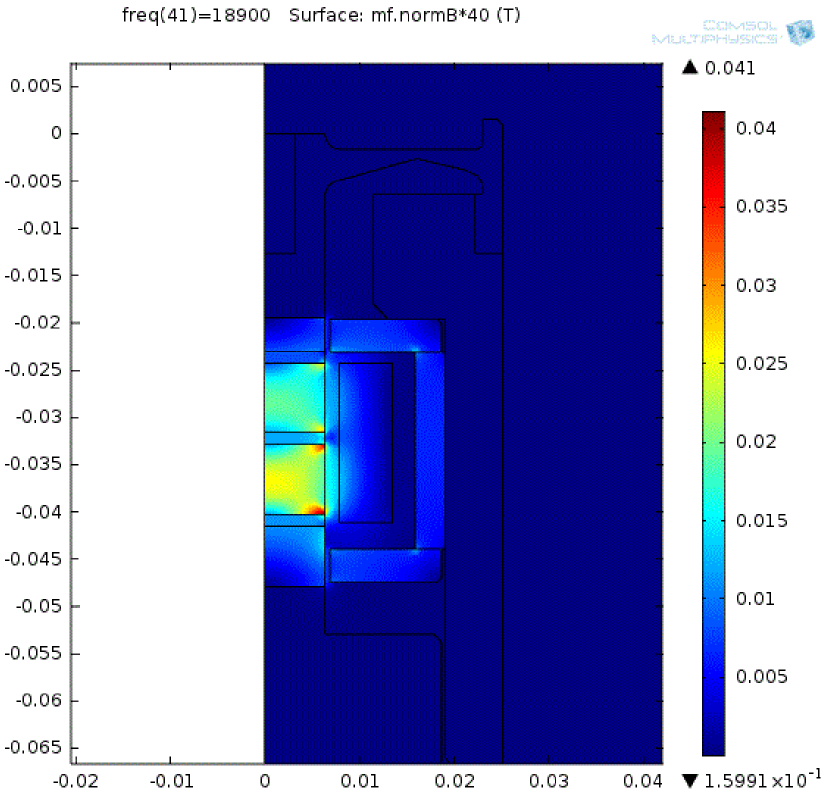


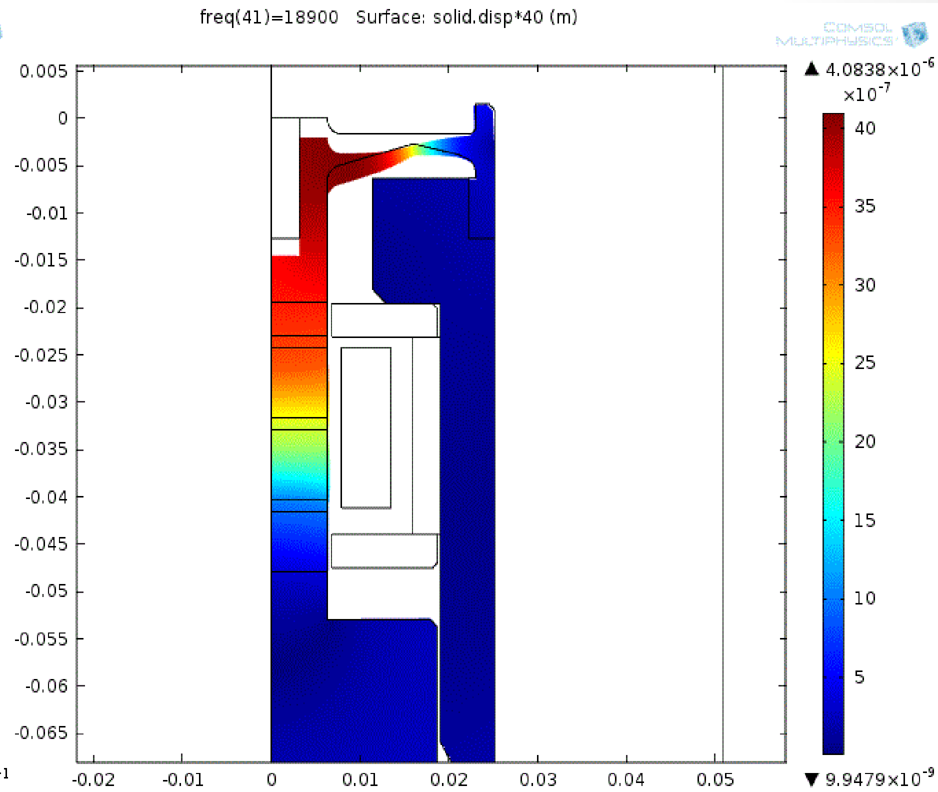
Model validation

- ETREMA Terfenol-D transducer - CU18A
  - 18 kHz nominal resonant frequency
  - 5 um (0-pk) displacement
- Significant amounts of performance data exist for this transducer
  - 100’s have been built and tested



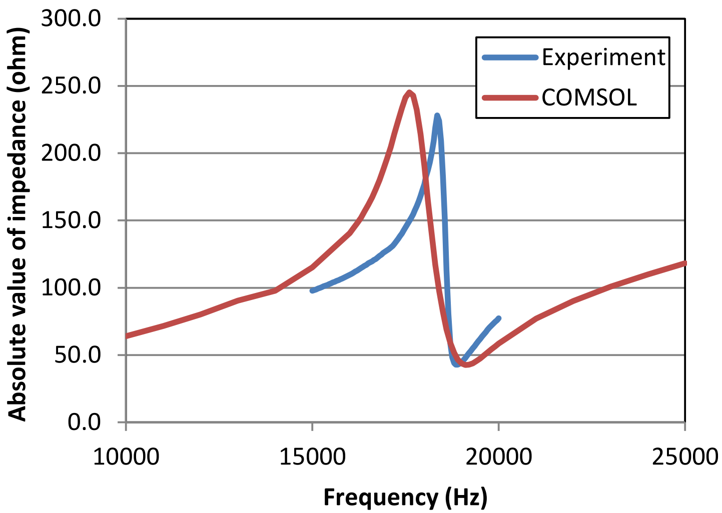
Magnetic fields and displacements

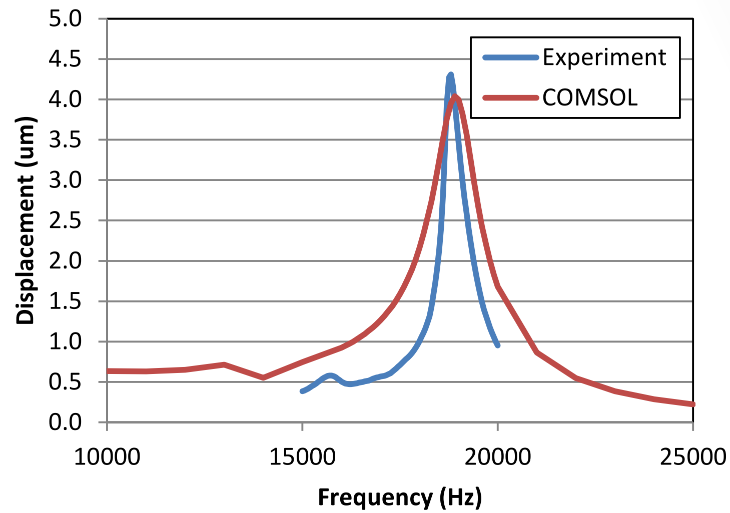


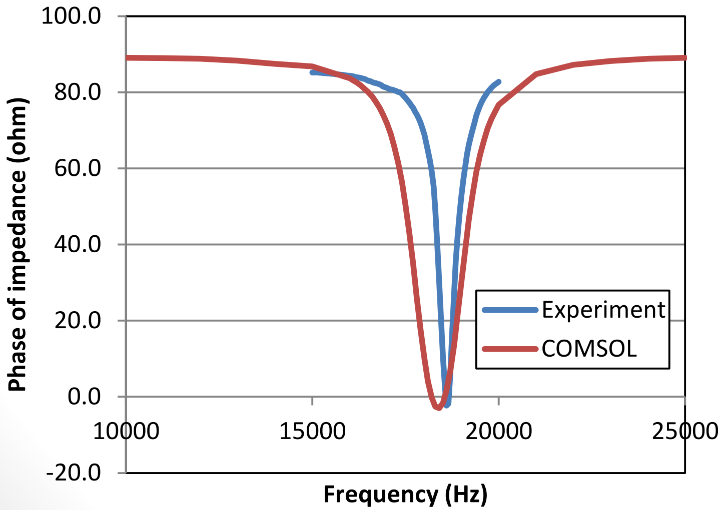


- Magnetic fields and displacements look quite reasonable
  - Magnetic fields are confined to the magnetic circuit
  - Flexure and output interface have the largest deflections for the transducer

Comparison with actual data







- Models of impedance and displacement were very similar to experimental results
- Two main sources of error
  - Material properties
  - Damping

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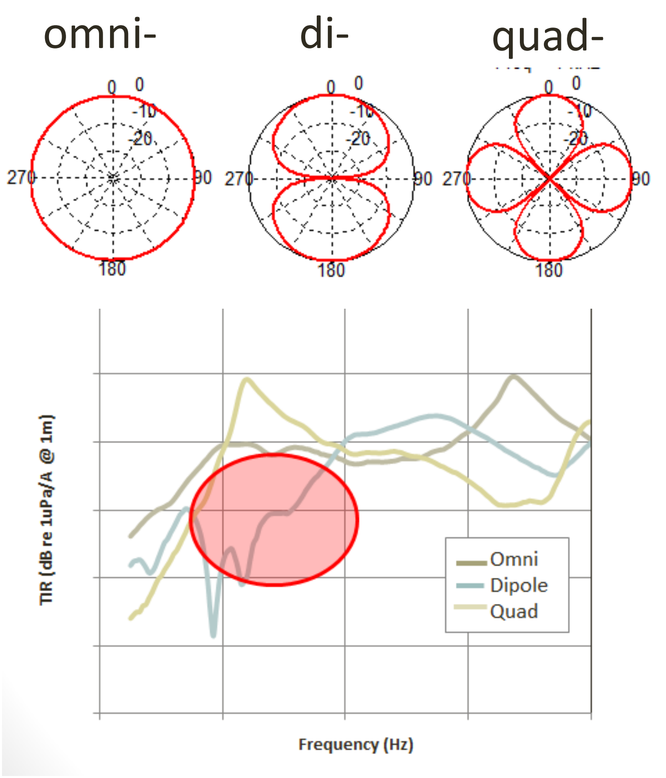
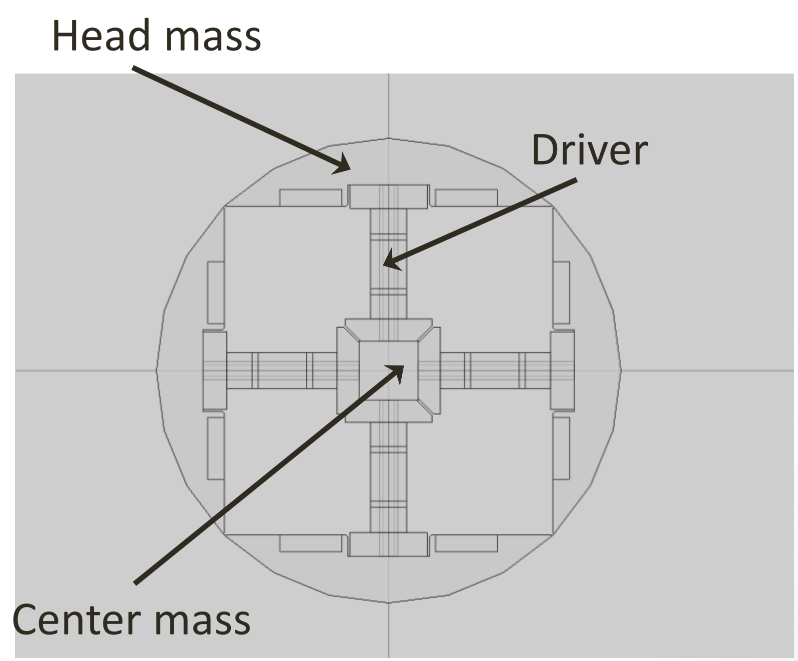
Design diagnosis

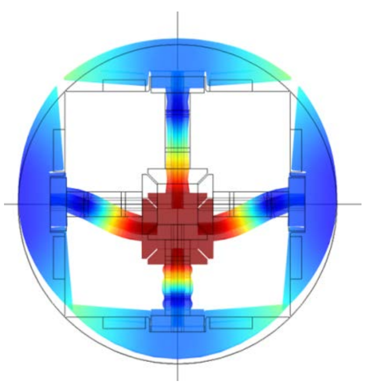
- SONAR projector
  - Three "modes" of operation: omnipole, dipole, quadrupole
  - One of the three modes, dipole, had very low acoustic output (-20 dB)

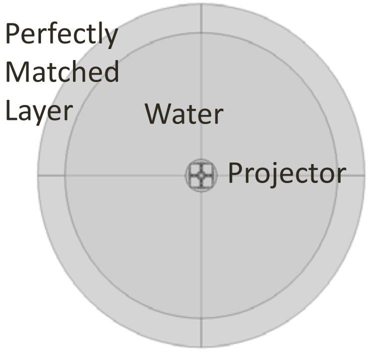


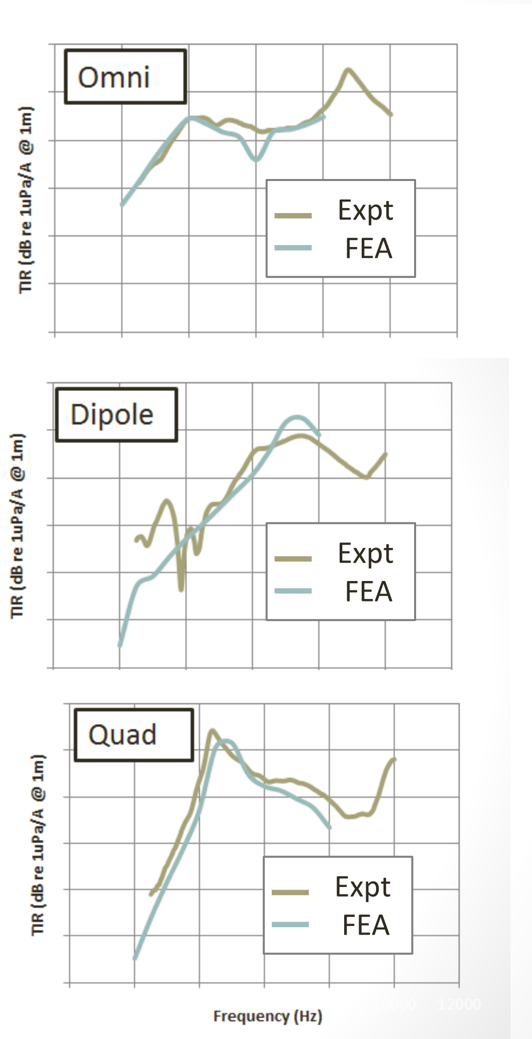


FEA models

- Coupled structural-acoustic models
- Single ring plus surrounding water
- No magnetostriction – too time intensive to solve
- Revealed a problem in the design







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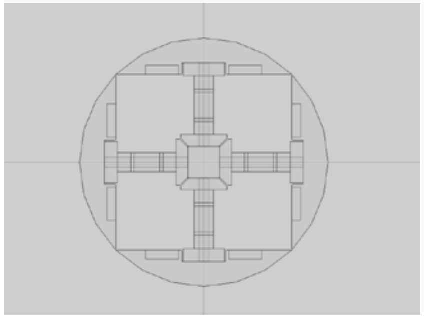
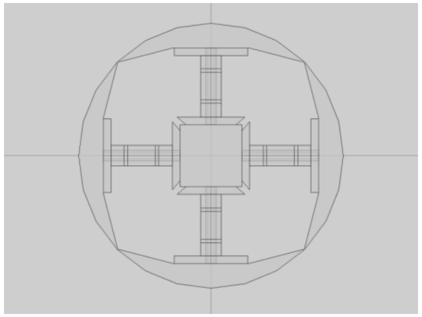
Problem resolution

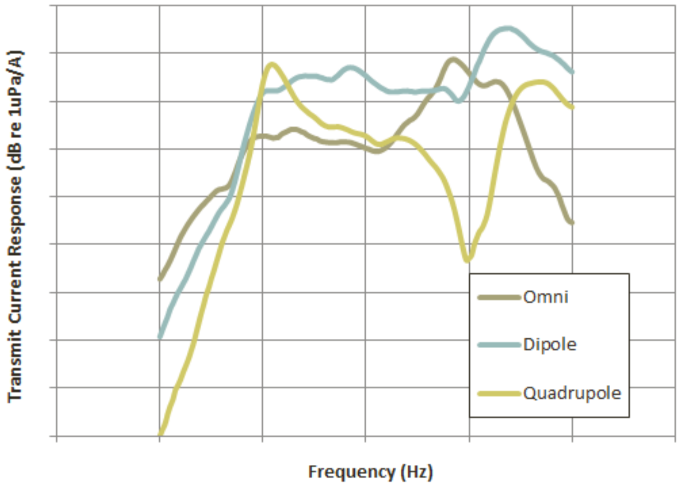
- FEA showed the cause of the low dipole output
- The design was modified to improve the response
- Experiments verified that the improved design operated as expected

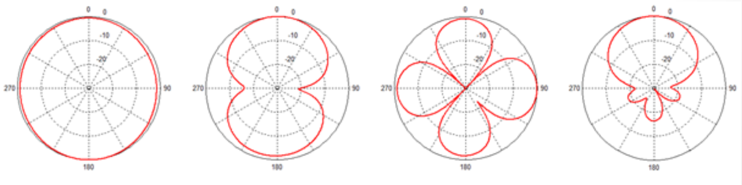


Flawed hardware



Corrected hardware





omni- di- quad- cardioid

Future modeling efforts

- Nonlinear fully-coupled magnetostrictive models
  - Some models have already been developed – need verification and additional material properties
  - Transducers which are not magnetically biased
  - Large-signal transducers which include hysteresis
  - Aid in developing closed-loop controls for specific applications
- Couple thermal effects with magnetostrictive models
  - Include temperature dependent material properties
  - Different time scale than magnetostrictive process
- Computer-driven optimization of designs
  - Optimize the amount of high-cost materials in transducers (magnetostrictive materials, permanent magnets, flux path materials, coils, etc.)
  - Improve performance, decrease cost, improve manufacturability

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Summary

- Fully coupled multiphysics simulation is a powerful tool for transducer design, evaluation, and optimization
  - Focus was on magnetostriction but all transducer technologies have coupled multiphysics (piezoelectric, electrostatic, electromagnetic, etc.)
- Finite element models can be used at different stages of product development
  - Design development
  - Existing product evaluation
  - Troubleshooting performance issues
- Resolving differences between models and experimental data is critical to continuous model improvement

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