National Aeronautics and Space Administration

Experimental comparison of piezoelectric and magnetostrictive shunt dampers

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Outline

- **Introduction**
  - Motivation, objectives, and scope
- **Experiment**
  - Load frame testing of shunt dampers
- **Results**
  - Frequency response comparison
- **Summary and conclusions**

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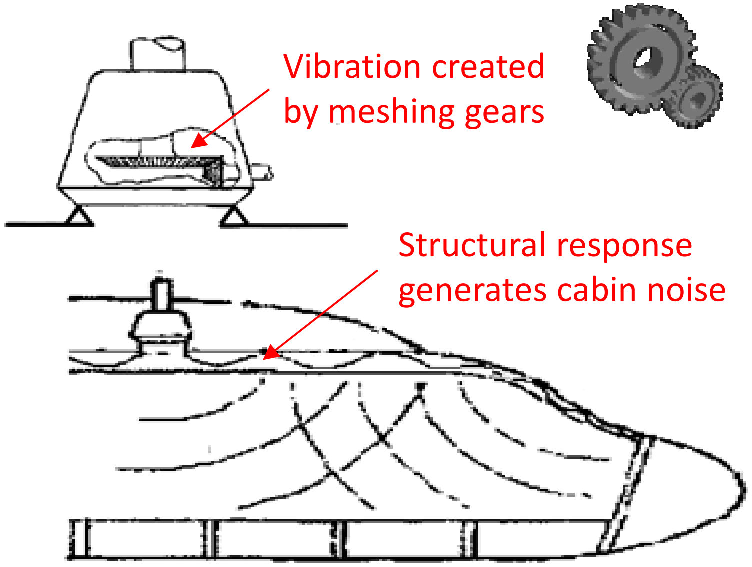
Driveline vibration effects

- Vibration is a side effect of transferring power through a rotating driveline.
- It causes functional issues, like reduced precision in cutting tools.
- Vibration generated by rotorcraft gearing causes cabin noise in excess of 100 dB!
- This environment prohibits widespread use of rotorcraft for civilian transportation.

Reduced cutting precision

Extreme noise levels in rotorcraft

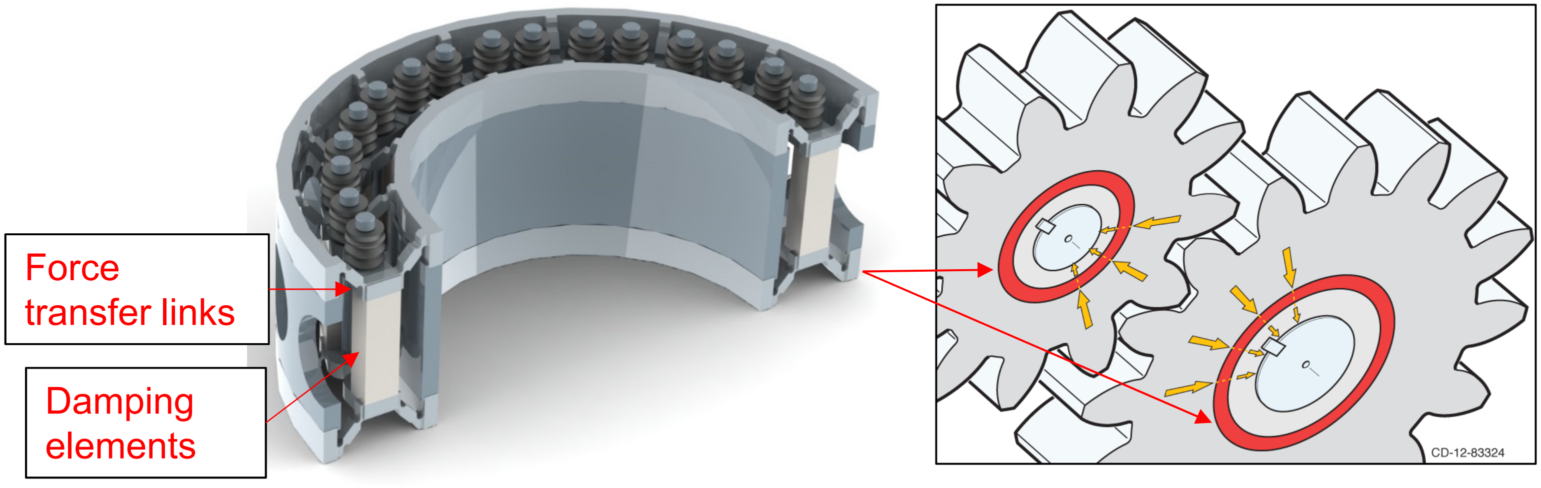
Sikorsky S-76



Vibration created by meshing gears

Structural response generates cabin noise

Driveline damping using the vibration ring



- The vibration ring is designed to incorporate damping elements into a driveline
- Force is transferred through the elements to create vibration isolation and damping
- Damping elements must have high stiffness to maintain the driveline alignment.

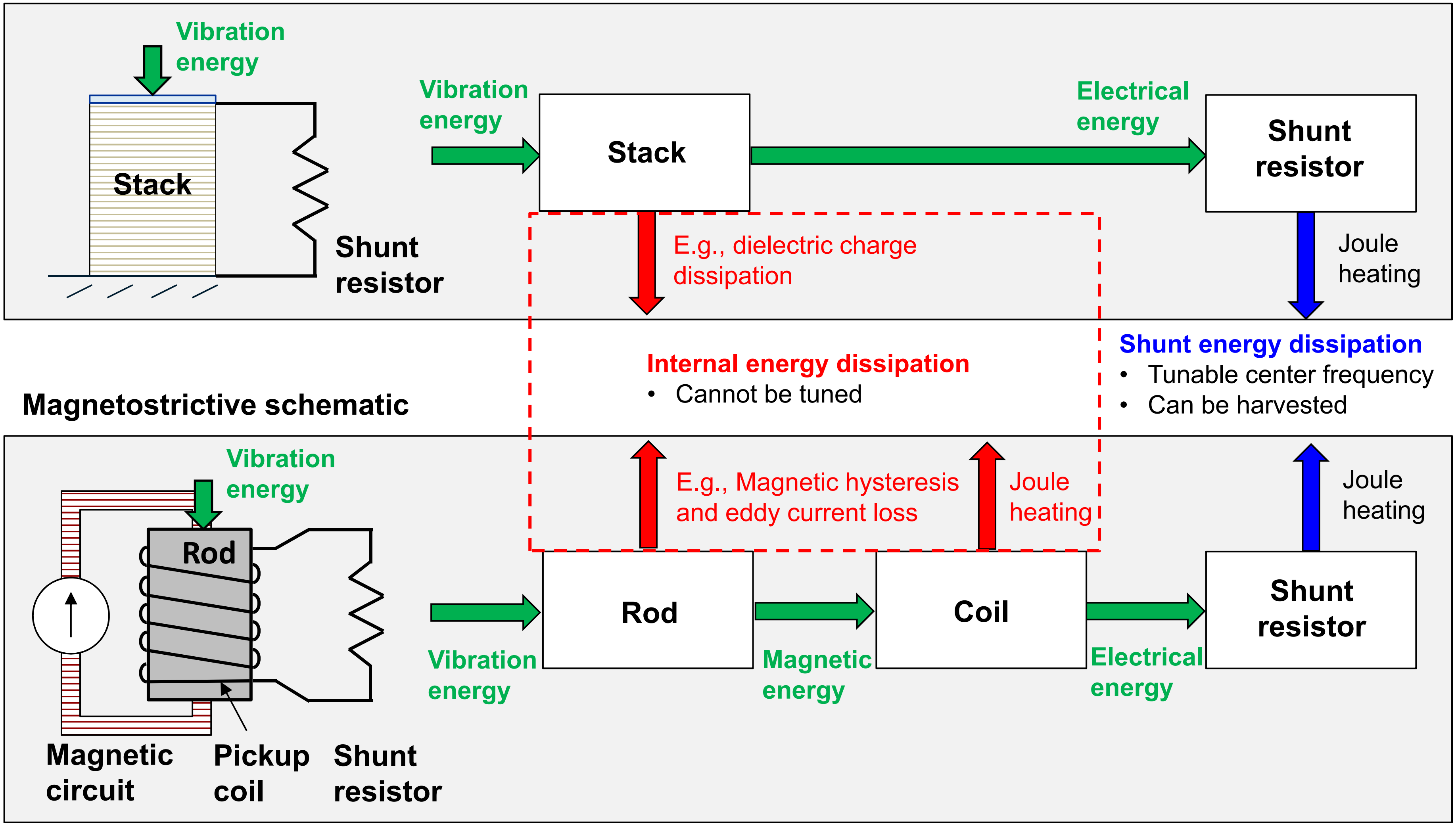
Material property comparison

Application	**Material**	**Modulus (GPa)**	***Loss factor***
Driveline components	Steel	200	0.0005
Vibration damping treatment	Rubber	0.05	0.50
Vibration ring damping elements	TBD	5 to 35	Maximize

Shunt damper options

- High stiffness smart materials: Piezoelectric ceramics and magnetostrictive metals
- Electrical ⇔ mechanical, Magnetic ⇔ mechanical

Piezoelectric schematic **Energy flow diagrams**



Internal energy dissipation
- Cannot be tuned

Shunt energy dissipation
- Tunable center frequency
- Can be harvested

Magnetostrictive schematic

Objectives and scope

- **Objective** : Characterize 3 candidate shunt damping devices
- Maximize damping at 750Hz
- Measure electro-mechanical response to vibratory force up 1000 Hz
    - Stiffness, damping
    - Internal vs. shunt energy dissipation

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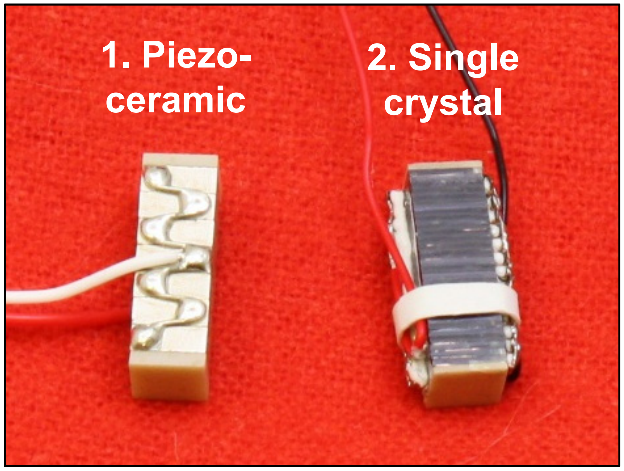
Test articles

Piezoelectric shunt dampers

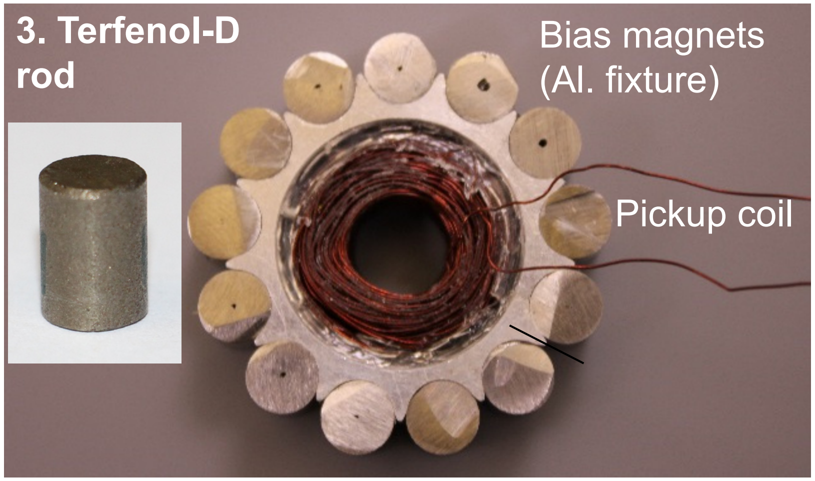


1. **Piezoceramic**: Soft-doped **polycrystalline** co-fired lead zirconate titanate (**PZT)**

2. **Single crystal:** Lead magnesium niobate-lead titanate (**PMN-30%PT**)

- Nominal: 5mm x 5mm x 16mm

Magnetostrictive shunt damper



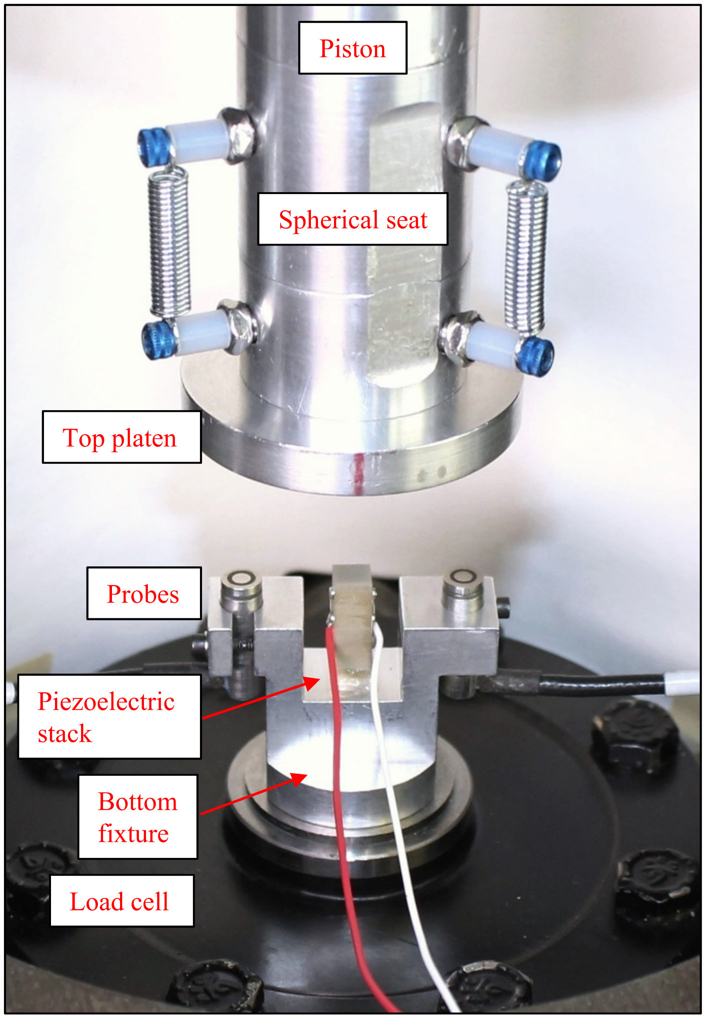
3. **Terfenol-D**

- Terbium, dysprosium and iron rod $(\mathrm{Tb_{0.3}Dy_{0.7}Fe_{1.92}})$
- Alnico grade 8 magnets
- Optimized (500-turn 30AWG) pickup coil
- Nominal: 7mm diameter, 10mm long

Test setup

Dynamic load frame assembly

-Piezoceramic case-



Provision to minimize error

- Even pressure on sample face
- Minimized inertial force error
- Magneto setup: Moving magnets
  - ➢ Attractive forces did not corrupt force
  - ➢ Did not generate voltage error
- **Sensor channels were phase aligned**

Removed data influenced by resonance

- Resonance at 1.0 to 1.2kHz
- Maximum data
  - ➢ Piezoceramic 923 Hz
  - ➢ Single crystal 804 Hz
  - ➢ Terfenol-D 350 Hz
    (higher harmonics)

Data processing

$$\textbf{Effective compressive modulus} = \left(\frac{\text{height}}{\text{area}}\right)\text{stiffness}$$

$$\textbf{Total loss factor} = \frac{\text{Total energy dissipated}/2\pi}{\text{Oscillation energy}} \left\{ \begin{array}{l} \textbf{Internal loss factor} = \dfrac{\text{Internal energy dissipated}/2\pi}{\text{Oscillation energy}} \\[2ex] \textbf{Shunt loss factor} = \dfrac{\text{Shunt energy dissipated}/2\pi}{\text{Oscillation energy}} \end{array} \right.$$

- Both contribute to damping
- High shunt loss factor required for tuning damping frequency or for energy harvesting

Test stages

1. **Optimize prestress**
   - Maximize energy conversion
2. **Optimizing resistance at 750Hz**
   - Maximize shunt loss factor

Refer to manuscript for details

3. **Measuring frequency response**
   - Optimal prestress & optimal shunt resistance
   - Frequency varied in steps from 2 Hz to 1000 Hz
   - Compute metrics

Discussed here

Nominal dynamic stress amplitude

Piezoceramic:	8.0 MPa
Single crystal:	4.0 MPa
Terfenol-D:	7.3 MPa

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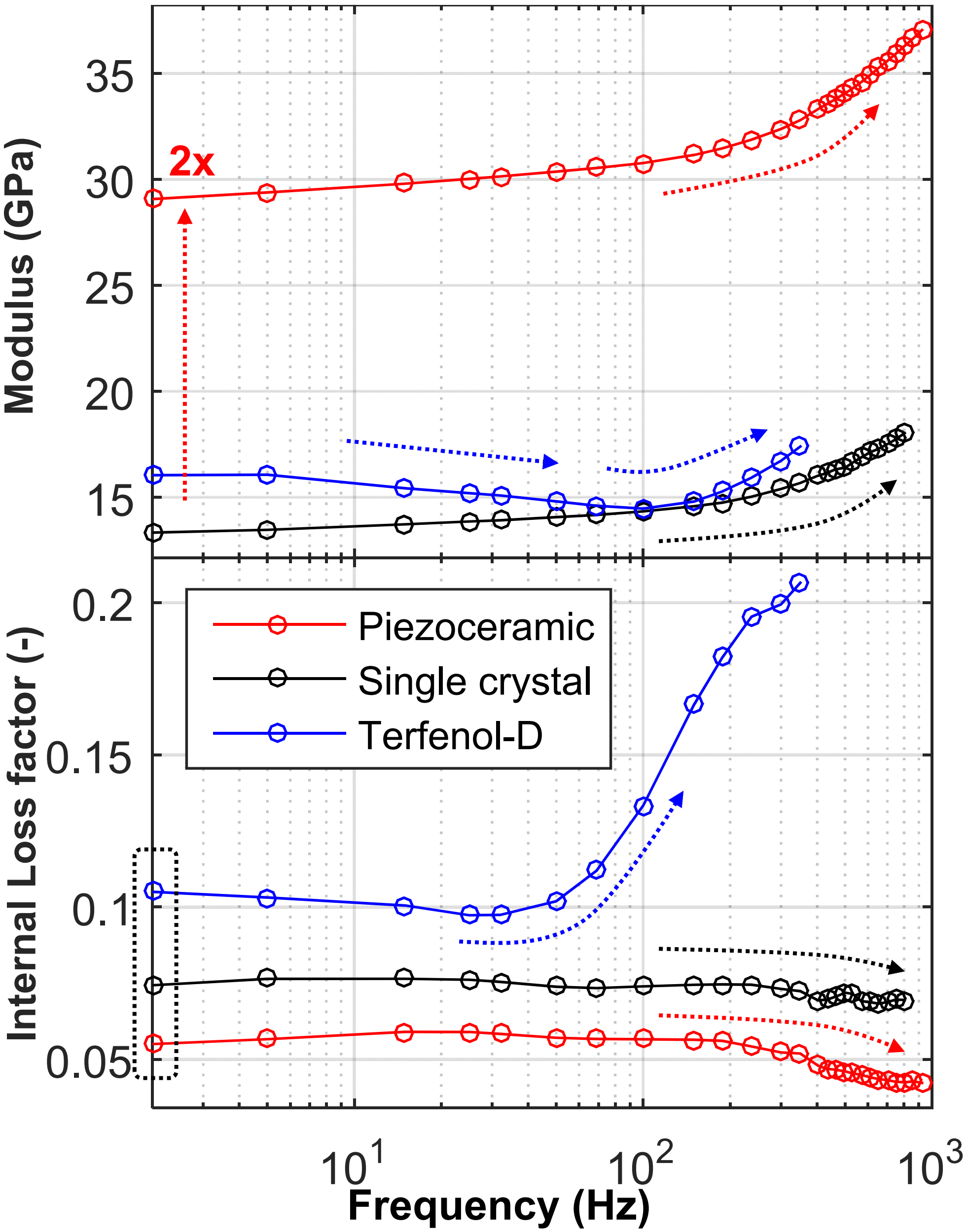
Frequency response (1 of 2)



Modulus

- Quasi-static: **Piezoceramic** roughly 2x **Single Crystal** and **Terfenol-D**
- **Piezoceramic** and **Single Crystal** trends: Increase with frequency. Expected based on electric-charge stiffening
- **Terfenol-D** trend: Decreases and then increases after 100 Hz. Increase is explained by magnetic field stiffening. Initial decrease is unexplained.

Internal loss factor

- Quasi-static: **Terfenol-D** > **Single crystal** > **Piezoceramic**
- **Piezoceramic** and **Single Crystal** trends: Slight inverse relationship with modulus.
- **Terfenol-D** trend: Unexpected, sharp increase after 30Hz. 3D COMSOL simulation indicates magnetic energy inducing eddy currents in aluminum magnet fixture

Frequency response (2 of 2)

Shunt loss factor

- Peak: Near 750Hz
  Single crystal > **Piezoceramic** > **Terfenol-D**

- **Piezoceramic** and **single crystal**:
  Peak shunt losses >> internal losses
  Potential for energy harvesting

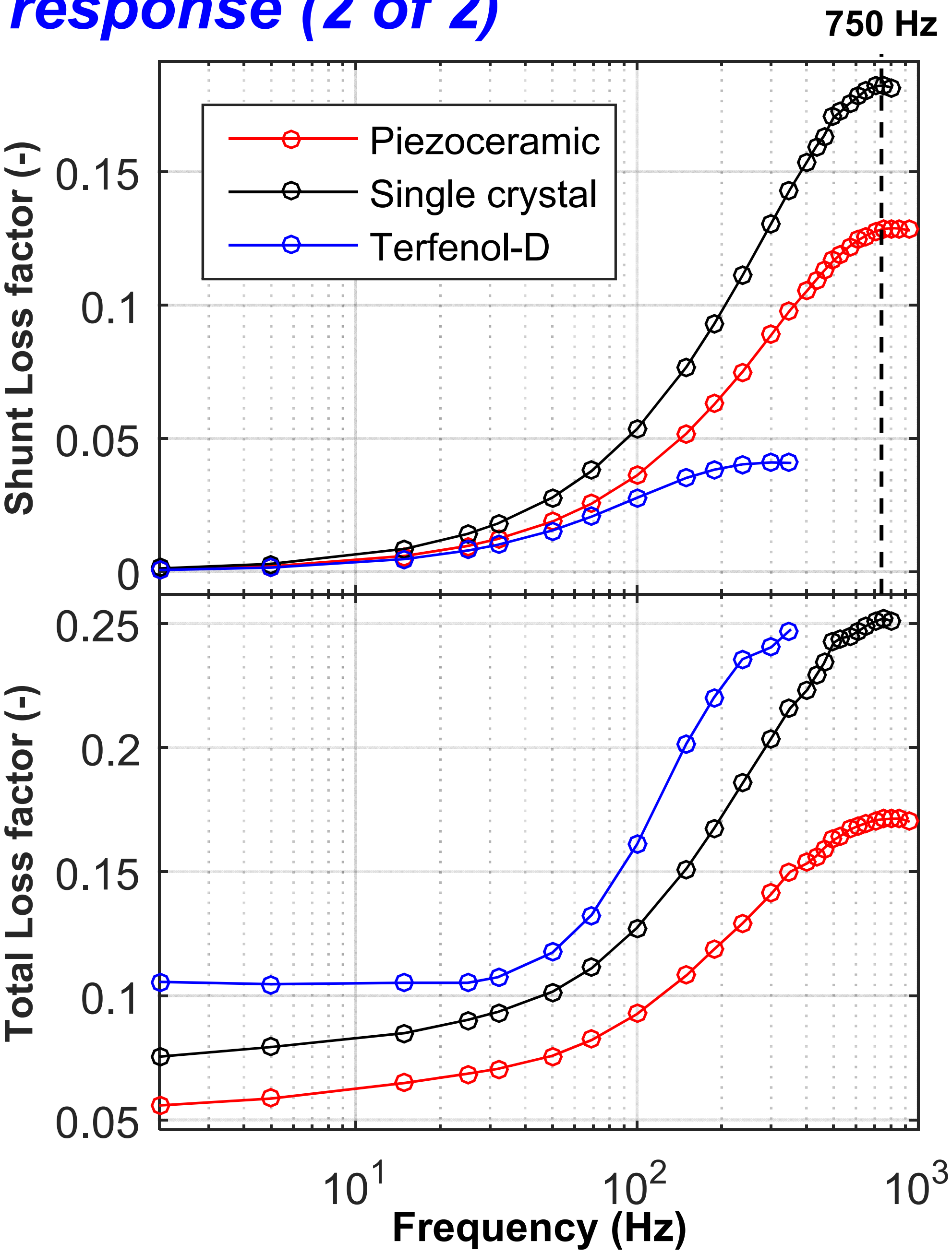
- **Terfenol-D**
  Relatively low shunt loss.
  Result of eddy current dissipation

Total loss factor

- All devices: Same order of magnitude as rubber.

- **Terfenol-D**

➢ Highest total loss across all frequencies
➢ Dominated by eddy current losses
  ○ Peak <u>not tunable</u>
  ○ Coil and shunt not needed



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Summary

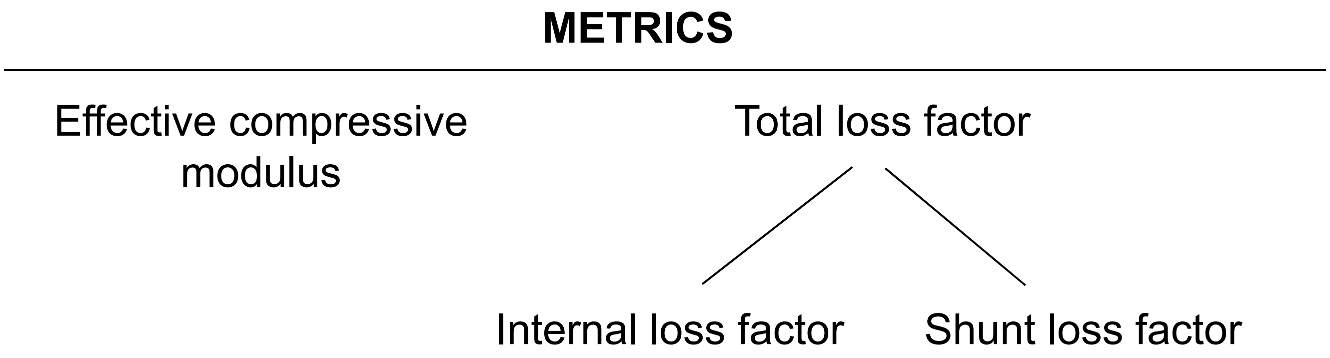
- Evaluated three high-stiffness shunt damping devices.

  Piezoelectric stacks
  - **Piezoceramic** (PZT)
  - **Single crystal** (PMN-30%PT)

  Magnetostrictive rod with pickup coil and bias magnets
  - **Terfenol-D** $(\mathrm{Tb_{0.3}Dy_{0.7}Fe_{1.92}})$

- Bias stress and shunt resistance were optimized for maximum damping at 750 Hz.

- Carefully controlled load frame experiments → dynamic force applied up to1000 Hz.



METRICS

Effective compressive modulus

Total loss factor

Internal loss factor

Shunt loss factor

Conclusions

- Unique/accurate data set for validating piezoelectric and magnetostrictive models.

- All devices: Reasonable for driveline damping application
  - Moduli 1 order of magnitude lower than steel (3 orders higher than rubber)
  - Loss factors on the same order as rubber

- **Single crystal:** Highest shunt loss factor- best tunable damper or energy harvester

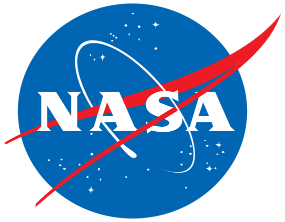
- **Terfenol-D**: Highest total loss factor- best non-tunable damper

  - Unintentional eddy current losses due to aluminum magnet holder

  - Reconfigure device in 2 ways

    1. Non-conductive magnet holder → increasing tuning and energy harvesting

    2. Get rid of coil and shunt → more compact/simpler device.
       Would continue to be an effective damper at high frequencies.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