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*
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

<table>
<thead>
<tr>
<th>Application</th>
<th>Material</th>
<th>Modulus (GPa)</th>
<th>Loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driveline components</td>
<td>Steel</td>
<td>200</td>
<td>0.0005</td>
</tr>
<tr>
<td>Vibration damping treatment</td>
<td>Rubber</td>
<td>0.05</td>
<td>0.50</td>
</tr>
<tr>
<td>Vibration ring damping elements</td>
<td>TBD</td>
<td>5 to 35</td>
<td>Maximize</td>
</tr>
</tbody>
</table>
Shunt damper options

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

Piezoelectric schematic

Energy flow diagrams

Magnetic circuit
Pickup coil
Shunt resistor

Rod
Coil
Shunt resistor

E.g., dielectric charge dissipation
E.g., Magnetic hysteresis and eddy current loss
Joule heating

Internal energy dissipation
- Cannot be tuned

Shunt energy dissipation
- Tunable center frequency
- Can be harvested
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 ($\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.92}$)
   - 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

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

Total loss factor = \frac{\text{Total energy dissipated}/2\pi}{\text{Oscillation energy}}

\begin{align*}
\text{Internal loss factor} & = \frac{\text{Internal energy dissipated}/2\pi}{\text{Oscillation energy}} \\
\text{Shunt loss factor} & = \frac{\text{Shunt energy dissipated}/2\pi}{\text{Oscillation energy}}
\end{align*}

• 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

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

Refer to manuscript for details

Nominal dynamic stress amplitude
- Piezoceramic:  8.0 MPa
- Single crystal:  4.0 MPa
- Terfenol-D:     7.3 MPa

Discussed here
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**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 not tunable
    - 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** \((\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_{1.92})\)

- Bias stress and shunt resistance were optimized for maximum damping at 750 Hz.
- Carefully controlled load frame experiments → dynamic force applied up to 1000 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
  o Moduli 1 order of magnitude lower than steel (3 orders higher than rubber)
  o 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
  o Unintentional eddy current losses due to aluminum magnet holder
  o **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.