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
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

- E.g., dielectric charge dissipation

Energy flow diagrams

- Internal energy dissipation
  - Cannot be tuned

Magnetostrictive schematic

- E.g., Magnetic hysteresis and eddy current loss

- Shunt energy dissipation
  - Tunable center frequency
  - Can be harvested

Experimental comparison of piezoelectric and magnetostrictive shunt dampers
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 (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 1.2 kHz
- 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}

\text{Total loss factor} = \frac{\text{Total energy dissipated}}{2\pi} \frac{1}{\text{Oscillation energy}}

\begin{align*}
\text{Internal loss factor} &= \frac{\text{Internal energy dissipated}}{2\pi} \frac{1}{\text{Oscillation energy}} \\
\text{Shunt loss factor} &= \frac{\text{Shunt energy dissipated}}{2\pi} \frac{1}{\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

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
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
    o Peak not tunable
    o 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

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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.