Experimental comparison of piezoelectric and magnetostrictive shunt dampers

Vivake M. Asnani
NASA Glenn Research Center
Materials and Structures Division, Rotating and Drive Systems Branch
Cleveland, OH 44135 USA, vivake.m.asnani@nasa.gov

Zhangxian Deng and Marcelo J. Dapino
NSF Industry & University Cooperative Research Center on Smart Vehicle Concepts
The Ohio State University, Department of Mechanical & Aerospace Engineering
Columbus, OH 43210 USA

Justin J. Scheidler
Universities Space Research Association at NASA Glenn Research Center
Materials and Structures Division, Rotating and Drive Systems Branch
Cleveland, OH 44135 USA

www.nasa.gov
Outline

• Introduction
  - Motivation, objectives, and scope

• Experiment
  - Load frame testing of shunt dampers

• Results
  - Frequency response comparison

• Summary and conclusions
Outline

• Introduction
  ➢ Motivation, objectives, and scope

• Experiment
  ➢ Load frame testing of shunt dampers

• Results
  ➢ Frequency response comparison

• Summary and conclusions
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

<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**

- **Stack Shunt**
  - Vibration energy
  - Stack
  - Shunt resistor
  - E.g., dielectric charge dissipation
  - Internal energy dissipation
  - Cannot be tuned
  - Internal energy dissipation
  - Cannot be tuned
  - Electromagnetic energy
  - Picked up coil
  - Magnetic energy

### Magnetostrictive schematic

- **Magnetic circuit**
  - Rod
  - Pick up coil
  - Shunt resistor
  - Electrical energy
  - Self-heating
  - E.g., magnetic hysteresis and eddy current loss
  - Can be harvested
  - Magnetic energy
  - Electrical energy
  - Self-heating

---

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
Outline

• Introduction
  ➢ Motivation, objectives, and scope

• Experiment
  ➢ Load frame testing of shunt dampers

• Results
  ➢ Frequency response comparison

• Summary and conclusions
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

Bias magnets (Al. fixture)

Pickup coil
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 energy dissipated \quad \text{Oscillation energy}

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

• Introduction
  ➢ Motivation, objectives, and scope

• Experiment
  ➢ Load frame testing of shunt dampers

• Results
  ➢ Frequency response comparison

• Summary and conclusions
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 30 Hz. 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  
    - Peak not tunable  
    - Coil and shunt not needed
Outline

• Introduction
  ➤ Motivation, objectives, and scope

• Experiment
  ➤ Load frame testing of shunt dampers

• Results
  ➤ Frequency response comparison

• Summary and conclusions
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**

<table>
<thead>
<tr>
<th>Effective compressive modulus</th>
<th>Total loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Internal loss factor</td>
</tr>
</tbody>
</table>


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.