Vibration control via stiffness switching of magnetostrictive transducers

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

Vivake M. Asnani  
NASA Glenn Research Center Materials & Structures Division  
Rotating & Drive Systems Branch  
Cleveland, OH 44135

Marcelo J. Dapino  
The Ohio State University Department of Mechanical & Aerospace Engineering  
Columbus, OH 43210

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Outline

• Introduction
• Development of lumped parameters model
  • Stiffness switching via controlled voltages
  • Stiffness switching via electrical shunting
• Vibration control law for stiffness switching
• Results: voltage-controlled stiffness switching
• Comparison to shunting techniques
• Summary and conclusions
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Introduction

Motivation

- Many power generation and transmission systems generate excessive noise and vibration
  - exacerbated by lightweighting
- Semi-active vibration control often relies on stiffness tuning
- Magnetostrictive transducer developed for real-time stiffness control

Objectives

- Apply the dynamically-tunable transducer to switched-stiffness vibration control
- Compare the performance to electrical shunting techniques

National aeronautics security goals

- reduce main rotor gearbox noise by 20 dB
- reduce vibratory loads by 30%
- reduce cabin noise below 77 dB

NASA’s Rotary Wing project goal

2. Subsonic Rotary Wing Project goals, 2011 ARMD Program and Project overview
Stiffness tuning of magnetostrictive materials

Material characteristics
- 2-way coupling of magnetic and mechanical states
- Non-contact operation, inherent active behavior, and no aging

Key properties of common magnetostrictive materials.

<table>
<thead>
<tr>
<th></th>
<th>Terfenol-D(^3)</th>
<th>Galfenol(^4,5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency bandwidth, Hz</td>
<td>(\approx 2e4)</td>
<td>(\approx 2e3)</td>
</tr>
<tr>
<td>Young’s Modulus, GPa (tunable range)</td>
<td>15–110</td>
<td>35–70</td>
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<td>Tensile strength, MPa</td>
<td>40</td>
<td>350</td>
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<td>0.7–0.8</td>
<td>0.6–0.7</td>
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<tr>
<td>Temp. limits, °C (lower/upper)</td>
<td>(&lt;-20 / 380)</td>
<td>(&lt;-20 / 670)</td>
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\[ \Delta E = \frac{E_{\text{max}} - E_{\text{min}}}{E_{\text{max}}} \]
\[ E = \text{Young’s modulus} \]

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Model development

- Newton’s 2\textsuperscript{nd} law coupled with nonlinear electromechanical transducer model
- Assumption: transducer has no internal loss
  - Terfenol-D selected over Galfenol
- Magnetostrictive force generated by current

Nonlinear constitutive model
\[
\Delta B = \mu^S \Delta H + d E^H \Delta S \\
\Delta T = -d E^H \Delta H + E^H \Delta S
\]
\(\mu^S, d, E^H\) functions of \(H, T\)

Magnetic field
\[
\Delta H = \frac{N}{l_c} \Delta i_c
\]

Transducer force
\[
\Delta F_{\text{trans}} = k^H \Delta x - \theta \Delta i_c
\]

Electromotive force
\[
\Delta V_{\text{emf}} = -N A_c \frac{d}{dt} (\Delta B) = -\frac{d}{dt} (\theta \Delta x + L_c^S \Delta i_c)
\]
Model development

Voltage-controlled stiffness

\[
\begin{align*}
\Delta V &= R_c \Delta i_c - \Delta V_{\text{emf}} \\
\begin{bmatrix}
\Delta x_1 \\
\Delta x_2 \\
\Delta i
\end{bmatrix} &= -
\begin{bmatrix}
0 & 1 & 0 \\
kH & c & -\theta \\
\dot{\theta} & \theta & \dot{L}^s + R_{\text{coil}}
\end{bmatrix}
\begin{bmatrix}
\Delta x_1 \\
\Delta x_2/m \\
\Delta i/L^s
\end{bmatrix} +
\begin{bmatrix}
0 \\
\Delta F \\
\Delta V
\end{bmatrix}
\end{align*}
\]

Shunt-controlled stiffness

\[
\begin{align*}
Z_{\text{sh}} \{\Delta i_{\text{sh}}\} - R_c \Delta i_c + \Delta V_{\text{emf}} &= 0 \\
\begin{bmatrix}
\Delta x_1 \\
\Delta x_2 \\
\Delta i
\end{bmatrix} &= -
\begin{bmatrix}
0 & 1 & 0 \\
kH & c & -\theta \\
\dot{\theta} & \theta & \dot{L}^s + R_{\text{coil}}
\end{bmatrix}
\begin{bmatrix}
\Delta x_1 \\
\Delta x_2/m \\
\Delta i/L^s
\end{bmatrix} +
\begin{bmatrix}
0 \\
\Delta F \\
\Delta V
\end{bmatrix}
\end{align*}
\]
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Switched-stiffness vibration control law

- Potential energy decreases at displacement maxima
- Switching bandwidth > 4 times vibration frequency

Stiffness tuning condition for each mechanical state.

Control logic.
Mechanical resonance induced by the control due to the magnetostrictive force.
Modified switched-stiffness vibration control law

Static equilibrium position

Tuning condition

Modified tuning conditions for control in presence of magnetostrictive force.

Young’s modulus (left) & electromechanical coupling coefficient (right) of Terfenol-D transducer at different bias magnetic fields.
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Voltage-controlled stiffness switching

- Control of undamped, free vibration studied
- $F_{\text{mag}}$ prevents complete vibration attenuation
- Performance may improve if current controlled

Controlled response 1: uncontrolled (-----) and controlled (-----).
Voltage-controlled stiffness switching

Controlled response 2: uncontrolled (---) and controlled (----).
Voltage-controlled stiffness switching

- Controlled response calculated after $F_{\text{mag}}$ artificially removed
- Effective viscous damping factors calculated by logarithmic decrement

<table>
<thead>
<tr>
<th>Controlled Response</th>
<th>Effective Viscous Damping Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>0.19</td>
</tr>
<tr>
<td>2 ($F_{\text{mag}}$ removed)</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Controlled response 2 with (---) and without (-----) $F_{\text{mag}}$. 

Graph showing the time domain response with and without magnetic force $F_{\text{mag}}$. The graph illustrates the damping effect when $F_{\text{mag}}$ is present and absent.
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Comparison to shunting techniques

- Voltage-controlled switching compared to...
  - Shunt-controlled switching
    - Open circuit to short circuit
    - Open circuit to optimal resistance
  - Optimal resistive shunt damping
- Performance of shunting techniques improves as coupling factor increases
  - Bias condition changed

Controlled response 1 compared to shunt-controlled stiffness switching and optimal shunt damping.
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Summary

- **Structural vibration control** via stiffness switching of magnetostrictive transducers
- **Nonlinear, electromechanical model** developed
  - Voltage control of stiffness
  - Shunt control of stiffness
- Control of **undamped, free vibration** studied
- **Modified control law** developed
- **Voltage-controlled switching** compared to shunt-controlled switching and shunt damping
## Conclusions

<table>
<thead>
<tr>
<th></th>
<th>Voltage switching</th>
<th>Shunt switching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus change</td>
<td>Large</td>
<td>Moderate</td>
</tr>
<tr>
<td>Need external power source?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Continuous stiffness tuning?</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Unwanted magnetostrictive force?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Unwanted parametric force?</td>
<td>No</td>
<td>No (resistive shunts) Yes (reactive shunts)</td>
</tr>
<tr>
<td>Complexity</td>
<td>Moderate</td>
<td>Simple to moderate</td>
</tr>
</tbody>
</table>

- Control performance may improve if current is controlled rather than voltage
- Voltage-controlled switching outperforms shunt-controlled switching due to $F_{mag}$
- Performance likely degrades when higher modes participate or feedback uncertainty exists
- Effect of internal energy losses should be studied
  - E.g., magnetic hysteresis, eddy currents, mechanical material damping
Extra slides.....
Magneetostrictive materials

- Atomic-scale coupling between orientation of non-spherical electron cloud and magnetic moment
- Inherent behavior below Curie temperature (300 to 700 °C)
- Man-made materials: Terfenol-D (TbDyFe) and Galfenol (FeGa)

Magnetic: \( \vec{B} = \mu^T \vec{H} + d \vec{T} \)
Mechanical: \( \vec{S} = d^T \vec{H} + s^H \vec{T} \)

- atom
- magnetic moment ("miniature magnet")
## Piezoelectric vs Magnetostrictive vs Magnetorheological (MR) Elastomer

<table>
<thead>
<tr>
<th>Property</th>
<th>Piezoelectric (PZT [1-3])</th>
<th>Magnetostrictive (Terfenol-D, Galfenol [4,5,27])</th>
<th>Magnetorheological (MR) Elastomer (MR rubber [6,24-26])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency bandwidth, Hz</td>
<td>≈1e6</td>
<td>≈1e4</td>
<td>&gt;1.4e3</td>
</tr>
<tr>
<td>Modulus, GPa (tunable range)</td>
<td>40–70</td>
<td>15–110</td>
<td>0.003–0.008</td>
</tr>
<tr>
<td>Loss factor (max)</td>
<td>0.25</td>
<td>0.27</td>
<td>&gt;0.13</td>
</tr>
<tr>
<td>Tensile strength, MPa</td>
<td>40</td>
<td>40</td>
<td>350</td>
</tr>
<tr>
<td>Fatigue strength*, MPa</td>
<td>–</td>
<td>–</td>
<td>75</td>
</tr>
<tr>
<td>Energy conversion factor</td>
<td>0.48–0.78</td>
<td>0.7–0.8</td>
<td>0.6–0.7</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>4.7–7.8</td>
<td>9.25</td>
<td>7.8</td>
</tr>
<tr>
<td>Temp. limits, °C (lower/upper)</td>
<td>-20 / 150–500</td>
<td>-20 / 380</td>
<td>-20 / 670</td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td>• Direct electrical control (compact)</td>
<td>• No permanent high temp. damage</td>
<td>• Can retro-fit into NVH devices</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>• Damaged at high temp.</td>
<td>• Require electromagnets</td>
<td>• Vulcanize in mag. field</td>
</tr>
</tbody>
</table>

* Fully reversed (R = -1)

---

**Table Notes:**
- **Piezoelectric:** PZT
- **Magnetostrictive:** Terfenol-D, Galfenol
- **Magnetorheological (MR) Elastomer:** MR rubber

---

**Pros:**
- Direct electrical control (compact)
- Approx. linear
- No permanent high temp. damage
- Can retro-fit into NVH devices

**Cons:**
- Damaged at high temp.
- Require electromagnets
- Vulcanize in mag. field
- Require electromagnets
<table>
<thead>
<tr>
<th>$dt$, $\mu$s</th>
<th>$m$, kg</th>
<th>$c$, Ns/m</th>
<th>$R_{\text{coil}}$, $\Omega$</th>
<th>$N$</th>
<th>$A_{\text{rod}}$, cm$^2$</th>
<th>$l_{\text{rod}}$, m</th>
<th>$T_{\text{bias}}$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>80</td>
<td>0</td>
<td>2.5</td>
<td>1840</td>
<td>1.27</td>
<td>0.144</td>
<td>-70</td>
</tr>
</tbody>
</table>
Effective Viscous Damping Factor

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Effective Viscous Damping Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switched voltage (controlled Response 1)</td>
<td>0.13</td>
</tr>
<tr>
<td>Switched shunt, open to short</td>
<td>0.20</td>
</tr>
<tr>
<td>Switched shunt, open to optimal resistance</td>
<td>0.17</td>
</tr>
<tr>
<td>Optimal resistive shunt damping</td>
<td>0.37</td>
</tr>
</tbody>
</table>
Magnetostrictive Variable-Stiffness Spring: Overview and Electromechanical Modeling

**Goal:** develop a device having a dynamically-tunable stiffness (DC to 1 kHz)

- **Constraints:** nominal axial stiffness (~500 N/μm), external geometry (50 mm diameter, 105 mm height)
- **Independent design variable:** length of the magnetostrictive rod
- Response to voltage excitation calculated using a fully-nonlinear, electromechanical transducer model
  - Eddy current effects neglected
- Blocked inductance ($L^S$) proportional to $N^2$ and blocked magnetic permeability ($\mu^S$)

\[
V(s) = Z_{\text{eff}} I(s) = \left[ (L^S s + R_{\text{coil}}) + \frac{\Theta^2 s}{ms^2 + K^H} \right] I(s)
\]

**Effective electrical impedance** (for mass loading)

\[
H(s) = \frac{N}{l_{\text{coil}}} I(s)
\]

**Current – Magnetic field relation**

\[
H(s) = \frac{N}{l_{\text{coil}} Z_{\text{eff}}} V(s)
\]

**Magnetic field response**

\[
\Theta = \frac{NdE^H A_{\text{rod}}}{l_{\text{coil}}}
\]

\[
L^S = \frac{N^2 \mu^S A_{\text{coil}}}{l_{\text{coil}}}
\]

Electromechanical transducer model (single-degree-of-freedom).
Magnetostrictive Variable-Stiffness Spring: Electromechanical modeling

- Varispring operated about a large compressive bias
  - stiff when $H = 0$, softens as $H \rightarrow H_{\text{max}}$
- Step change in field (stiffness) calculated as the response to step change in voltage
  - Galfenol or Terfenol-D, 3 electromagnet wire gauges
  - Minimum blocked inductance (minimum number of electromagnet windings $N$) for each case
- Faster response using Terfenol-D (lower $\mu^s$) and larger wires (lower $N$)

Rise time (left) and average power (right) required to reach tuning field with a 250 V step voltage; $m = 2$ kg, equal modulus change
Magnetostrictive Variable-Stiffness Spring: Magnetic Diffusion and Internal Mass Effect

- Terfenol-D $f_c$ two orders of magnitude larger than for Galfenol
- Experimental objective: measure stiffness change due to elastic modulus change
- Lumped parameter model used
  - Worst-case conditions considered
- Mass effect is < 3% in both materials

**Magnetic diffusion cut-off frequency** for solid and laminated rods.

\[
\sigma_{\text{eff}} = \frac{\sigma}{(n+1)^2}
\]

Worst-case percent change in rod’s dynamic stiffness, $E^H = E_{\min}^H$, $f = 1 \text{kHz}$. 

Lumped parameter model
Magnetostrictive Variable-Stiffness Spring: Design

- Terfenol-D selected for improved rise time, diffusion cut-off frequency, and static elastic modulus range
Magnetostrictive Variable-Stiffness Spring: Design

- Terfenol-D rod laminated for improved dynamic performance
- Performance improved for shorter Terfenol-D rod; 2.4 cm (0.95 in) selected
- Inertial force error ≈ 0.2%
- Capacitive sensors measured displacement of Varispring