Vibration control via stiffness switching of magnetostrictive transducers

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Acknowledgements:
• NASA Revolutionary Vertical Lift Technology Project
• NASA Aeronautics Scholarship Program
• NSF I/UCRC on Smart Vehicle Concepts
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\textsuperscript{1} 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\textsuperscript{2} reduce main rotor gearbox noise by 20 dB
reduce vibratory loads by 30%
reduce cabin noise below 77 dB

\textsuperscript{1} Security and Homeland Defense Goal #2, 2010 National Aeronautics R&D Plan
\textsuperscript{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\textsuperscript{3}</th>
<th>Galfenol\textsuperscript{4,5}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency bandwidth, Hz</td>
<td>\approx 2e4</td>
<td>\approx 2e3</td>
</tr>
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<td>Young’s Modulus, GPa (tunable range)</td>
<td>15–110</td>
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<td>Temp. limits, °C (lower/upper)</td>
<td>&lt;-20 / 380</td>
<td>&lt;-20 / 670</td>
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Stiffness tuning overview.

<table>
<thead>
<tr>
<th></th>
<th>Device</th>
</tr>
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<tbody>
<tr>
<td>Tuning</td>
<td>vary voltage (V)</td>
</tr>
<tr>
<td>Metrics</td>
<td>\Delta E \approx 86%</td>
</tr>
<tr>
<td></td>
<td>+ 49% to 64% theoretically possible\textsuperscript{3,4}</td>
</tr>
</tbody>
</table>

\begin{align*}
\Delta E &= \frac{E_{\text{max}} - E_{\text{min}}}{E_{\text{max}}} \\
E &= \text{Young’s modulus}
\end{align*}

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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:
\[
\begin{align*}
\Delta B &= \mu^S \Delta H + d E^H \Delta S \\
\Delta T &= -d E^H \Delta H + E^H \Delta S
\end{align*}
\]
\(\mu^S, d, E^H\) 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
\[
\Delta V_{\text{emf}} = -N A_c \frac{d}{dt} (\Delta B) = -\frac{d}{dt} \left( \theta \Delta x + L^S_c \Delta i_c \right)
\]
Model development

Voltage-controlled stiffness

\[ F_{\text{vari}} \]

\[ i \]

\[ V \]

\[ i_{\text{sh}} \]

\[ Z_{\text{sh}} \]

\[ m \]

\[ \uparrow x \]

\[ F \]

\[ \Delta V = R_c \Delta i_c - \Delta V_{\text{emf}} \]

Electrical response

\[
\begin{cases}
\Delta \dot{x}_1 = 0 \quad 1 \quad 0 \\
\Delta \dot{x}_2 = k^H \quad c \quad -\theta \\
\Delta i = \dot{\hat{\theta}} \quad \theta \quad \dot{\hat{L}}^s + R_{\text{c}} + R_{\text{sh}} \\
\end{cases}
\]

\[
\begin{bmatrix}
\Delta x_1 \\
\Delta x_2/m \\
\Delta i/L^s \\
\end{bmatrix} +
\begin{bmatrix} 0 \\
\Delta F \end{bmatrix}
\]

Shunt-controlled stiffness

\[ F_{\text{vari}} \]

\[ i \]

\[ i_c \]

\[ i_{\text{sh}} \]

\[ Z_{\text{sh}} \]

\[ m \]

\[ \uparrow x \]

\[ F \]

\[ \Delta V = R_c \Delta i_c - \Delta V_{\text{emf}} \]

Electrical response

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\end{cases}
\]

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\begin{bmatrix}
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\Delta x_2/m \\
\Delta i/L^s \\
\end{bmatrix} +
\begin{bmatrix} 0 \\
\Delta F \end{bmatrix}
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Switched-stiffness vibration control law

Static equilibrium position

Tuning condition

\[ k = k_{\text{max}} \quad k = k_{\text{min}} \quad k = k_{\text{max}} \quad k = k_{\text{min}} \]

Stiffness tuning condition for each mechanical state.

- Potential energy decreases at displacement maxima
- Switching bandwidth > 4 times vibration frequency
Mechanical resonance induced by the control due to the magnetostrictive force.
Modified switched-stiffness vibration control law

Modified tuning conditions for control in presence of magnetostrictive force.

\[ k = k_{\text{max}} \quad F_{\text{mag}} < 0 \]

\[ k = k_{\text{min}} \quad F_{\text{mag}} > 0 \]

\[ k = k_{\text{max}} \quad F_{\text{mag}} > 0 \]

\[ k = k_{\text{min}} \quad F_{\text{mag}} > 0 \]

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>Controlled Response 1</td>
<td>0.25</td>
</tr>
<tr>
<td>Controlled Response 2</td>
<td>0.19</td>
</tr>
<tr>
<td>Controlled Response 2 ($F_{\text{mag}}$ removed)</td>
<td>0.02</td>
</tr>
</tbody>
</table>
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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)</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 $F_{\text{mag}}$
- 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.....
Magnetostrictive 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)

\[ \vec{B} = \mu^T \vec{H} + d \vec{T} \] (sensing)

\[ \vec{S} = d^T \vec{H} + s^H \vec{T} \] (actuation, \( \lambda \))

- atom
- magnetic moment ("miniature magnet")
<table>
<thead>
<tr>
<th></th>
<th>Piezoelectric</th>
<th>Magnetostrictive [4,5,27]</th>
<th>Magnetorheological (MR) elastomer</th>
<th>MR rubber [6,24-26]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency bandwidth, Hz</td>
<td>(\approx 1e6)</td>
<td>(\approx 1e4)</td>
<td>(\approx 2e3)</td>
<td>(&gt;1.4e3)</td>
</tr>
<tr>
<td>Modulus, GPa (tunable range)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young's Shear</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>40–70</td>
<td>15–110</td>
<td>35–70</td>
<td>0.003–0.008</td>
</tr>
<tr>
<td>Shear</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.005–0.008</td>
</tr>
<tr>
<td>Loss factor (max)</td>
<td>0.25</td>
<td>0.27</td>
<td>&gt;0.13</td>
<td>&gt;0.23</td>
</tr>
<tr>
<td>Tensile strength, MPa</td>
<td>40</td>
<td>40</td>
<td>350</td>
<td>6.5</td>
</tr>
<tr>
<td>Fatigue strength*, MPa</td>
<td>–</td>
<td>–</td>
<td>75</td>
<td>–</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>
<td>–</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>4.7–7.8</td>
<td>9.25</td>
<td>7.8</td>
<td>(\approx 2.8)</td>
</tr>
<tr>
<td>Temp. limits, °C (lower/upper)</td>
<td>(-20 / 150–500)</td>
<td>(-20 / 380)</td>
<td>(-20 / 670)</td>
<td>(-51 / 121)</td>
</tr>
<tr>
<td>Pros</td>
<td>• Direct electrical control (compact)</td>
<td>• No permanent high temp. damage</td>
<td>• Can retro-fit into NVH devices</td>
<td></td>
</tr>
<tr>
<td>Cons</td>
<td>• Damaged at high temp.</td>
<td>• Require electromagnets</td>
<td>• Vulcanize in mag. field</td>
<td></td>
</tr>
</tbody>
</table>

* Fully reversed (\(R = -1\))
Table 1: Model parameters for switched-stiffness vibration control modeling.

<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>Description</th>
<th>Value</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 ($\mu^S$)

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

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

**Current – Magnetic field relation**

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

$$\Theta = \frac{N d E^H A_{\text{rod}}}{l_{\text{coil}}}$$

**Magnetic field response**

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

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

**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 $H \to H_{\text{max}}$
- 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.

Laminated rod

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

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