Vibration control via stiffness switching of magnetostrictive transducers

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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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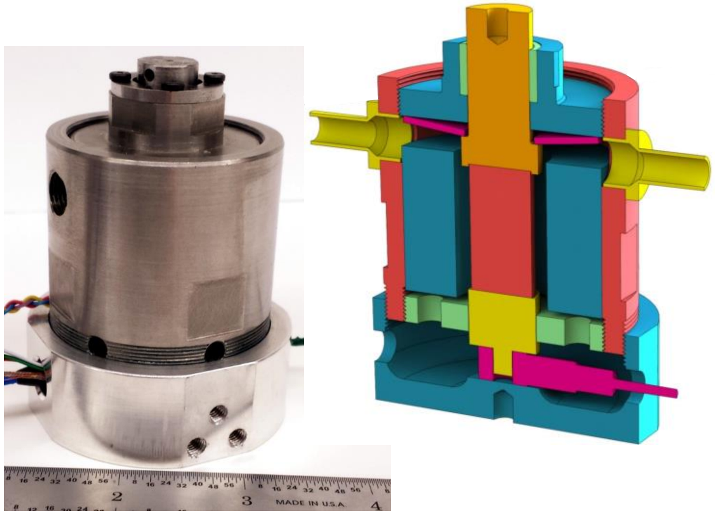
Introduction

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[1]	reduce main rotor gearbox noise by 20 dB
	reduce vibratory loads by 30%
NASA's Rotary Wing project goal[2]	reduce cabin noise below 77 dB

1. Security and Homeland Defense Goal #2, 2010 National Aeronautics R&D Plan
2. Subsonic Rotary Wing Project goals, 2011 ARMD Program and Project overview

Stiffness tuning of magnetostrictive materials

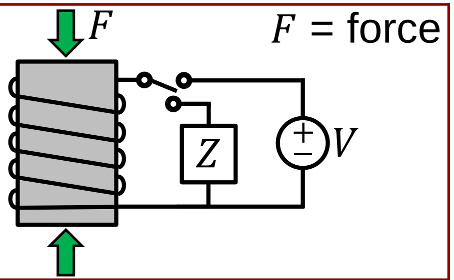
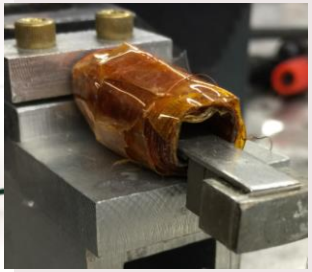
Material characteristics

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

Key properties of common magnetostrictive materials.

	Terfenol-D[3]	**Galfenol**[4,5]
Frequency bandwidth, Hz	≈2e4	≈2e3
Young's Modulus, GPa (tunable range)	15–110	35–70
Tensile strength, MPa	40	350
Energy conversion factor	0.7–0.8	0.6–0.7
Temp. limits, °C (lower/upper)	<-20 / 380	<-20 / 670

Stiffness tuning overview.

Schematic	 F = force	
Device		
Tuning	vary voltage (V)	vary impedance (Z)
Metrics	$\Delta E \approx 86\%$	$\Delta E \approx 29\%^{+}$

$^{+}$ 49% to 64% theoretically possible[3,4]

Metric

$$\Delta E = \frac{E_{max} - E_{min}}{E_{max}}$$

E = Young's modulus

3. ETREMA Products, Inc., "Terfenol-D physical properties," online, 2015.
4. ETREMA Products, Inc., "Galfenol physical properties," online, 2015.
5. Atulasimha, J. & Flatau, A.B., Smart Mater. & Struct. 20(4), 2011.

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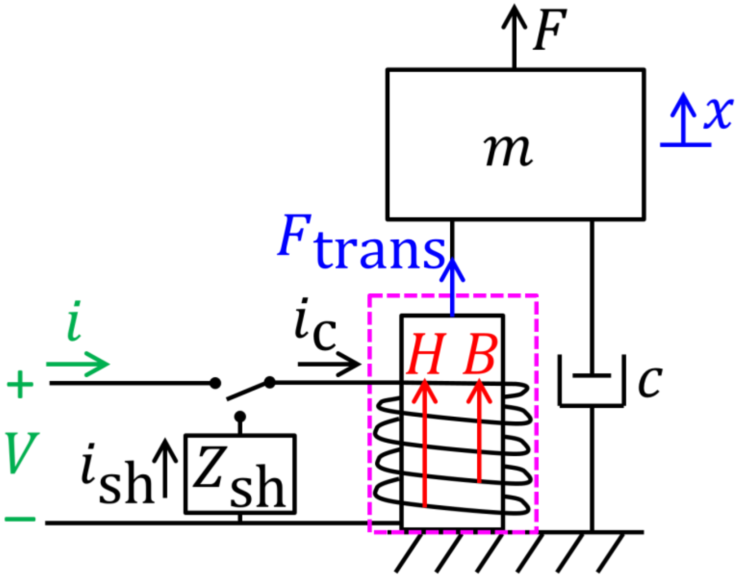
Model development

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



Mechanical system with magnetostrictive transducer (⬚).

Nonlinear constitutive model

$$\boxed{\begin{aligned}\Delta B &= \mu^S \Delta H + dE^H \Delta S \\ \Delta T &= -dE^H \Delta H + E^H \Delta S\end{aligned}}$$

μ^S, d, E^H functions of H, T

Magnetic field

$$\boxed{\Delta H = \frac{N}{l_c}\Delta i_c}$$

Transducer force

$$\boxed{\Delta F_{\text{trans}} = k^H \Delta x \boxed{-\theta \Delta i_c}}$$

magnetostrictive force ΔF_{mag}

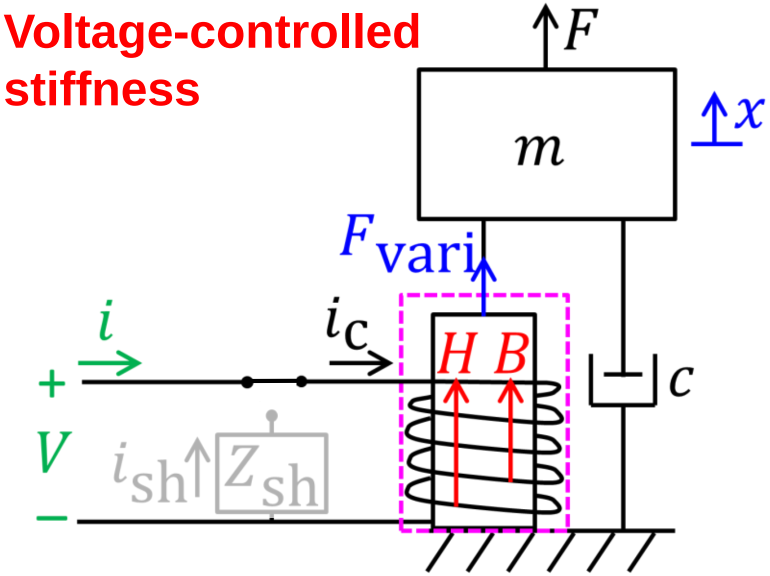
electromechanical coupling coefficient

Electromotive force

$$\boxed{\Delta V_{\text{emf}} = -NA_c \frac{d}{dt}(\Delta B) = -\frac{d}{dt}(\theta \Delta x + L_c^S \Delta i_c)}$$

Model development

Voltage-controlled stiffness

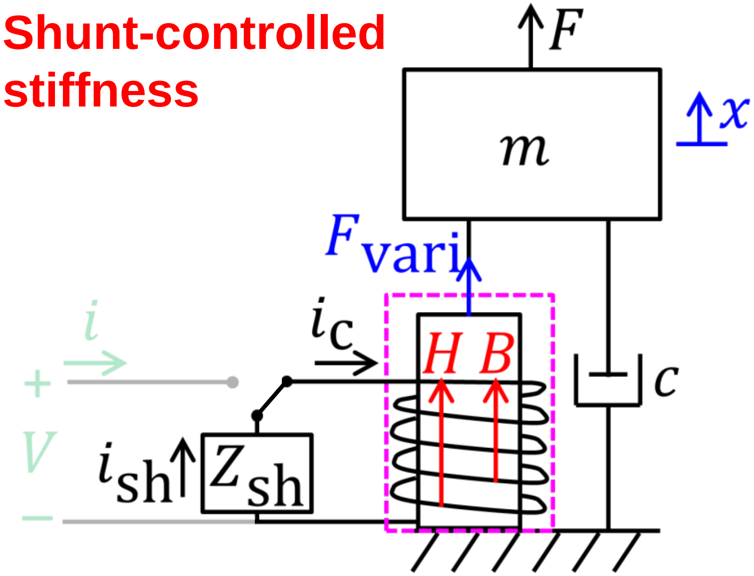


Electrical response

$$\boxed{\Delta V = R_c \Delta i_c - \Delta V_{\text{emf}}}$$

$$\begin{Bmatrix}\Delta\dot{x}_1\\ \Delta\dot{x}_2\\ \Delta\dot{i}\end{Bmatrix} = -\begin{bmatrix}0 & 1 & 0\\ k^H & c & -\theta\\ \dot{\theta} & \theta & \dot{L}^S + R_{\text{coil}}\end{bmatrix}\begin{Bmatrix}\Delta x_1\\ \Delta x_2/m\\ \Delta i/L^S\end{Bmatrix} + \begin{Bmatrix}0\\ \Delta F\\ \Delta V\end{Bmatrix}$$

Shunt-controlled stiffness



Electrical response

$$\boxed{Z_{\text{sh}}\{\Delta i_{\text{sh}}\} - R_c \Delta i_c + \Delta V_{\text{emf}} = 0}$$

$$\begin{Bmatrix}\Delta\dot{x}_1\\ \Delta\dot{x}_2\\ \Delta\dot{i}\end{Bmatrix} = -\begin{bmatrix}0 & 1 & 0\\ k^H & c & -\theta\\ \dot{\theta} & \theta & \dot{L}^S + R_c + R_{\text{sh}}\end{bmatrix}\begin{Bmatrix}\Delta x_1\\ \Delta x_2/m\\ \Delta i/L^S\end{Bmatrix} + \begin{Bmatrix}0\\ \Delta F\\ 0\end{Bmatrix}$$

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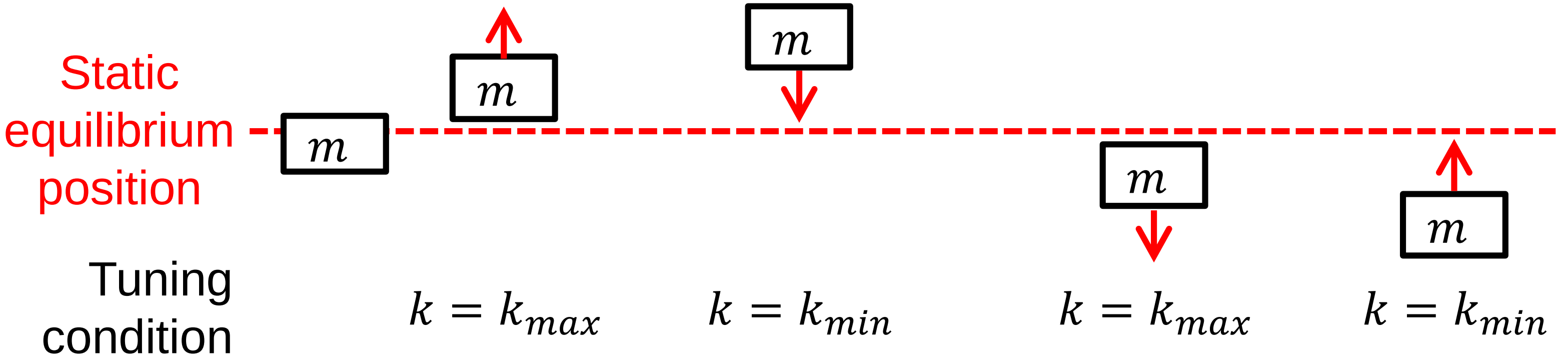
Switched-stiffness vibration control law



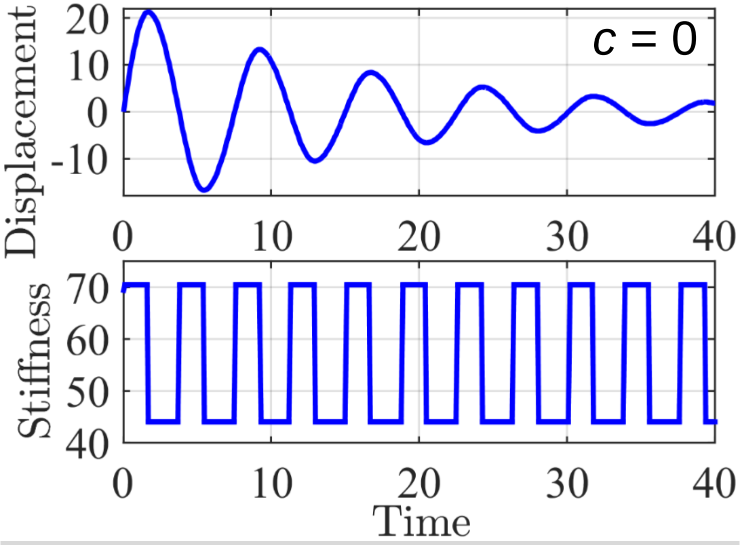
Static equilibrium position

Tuning condition

$k = k_{max}$ $k = k_{min}$ $k = k_{max}$ $k = k_{min}$

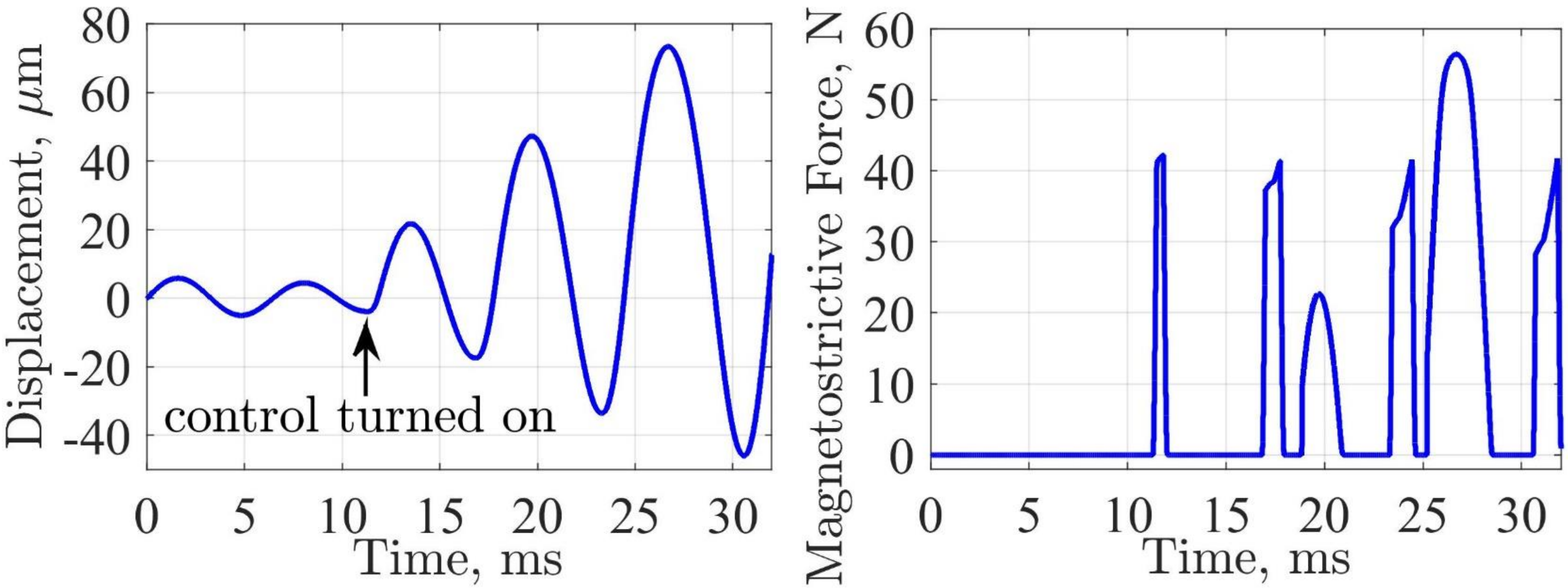
Stiffness tuning condition for each mechanical state.

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



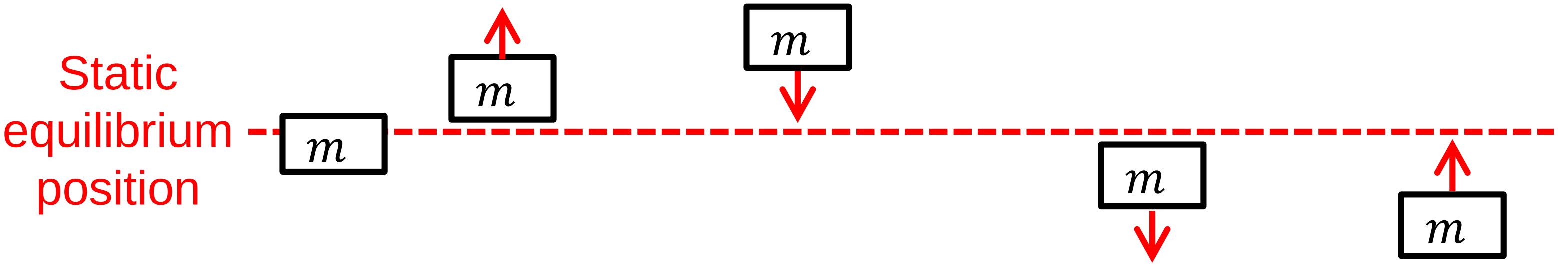
Control logic.

Switched-stiffness vibration control



Mechanical resonance induced by the control due to the magnetostrictive force.

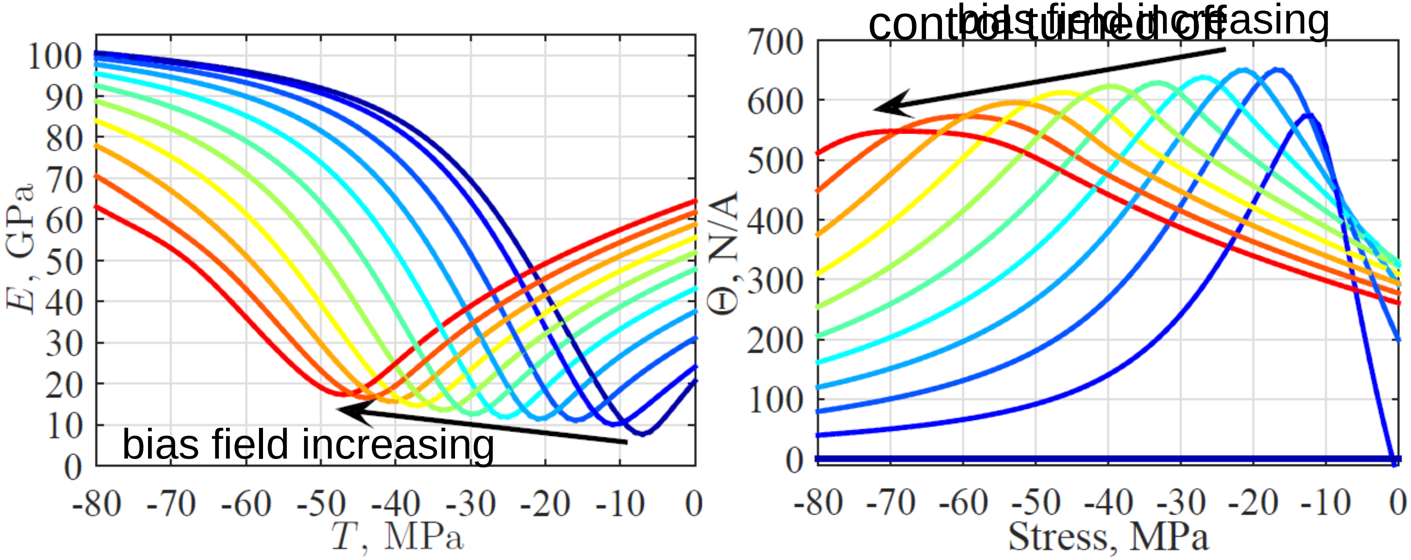
Modified switched-stiffness vibration control law



Tuning condition	ideal	$k = k_{max}$ $F_{mag} < 0$	$k = k_{min}$ $F_{mag} < 0$	$k = k_{max}$ $F_{mag} > 0$	$k = k_{min}$ $F_{mag} > 0$
	actual	$k = k_{max}$ $F_{mag} < 0$	$k = k(H_{bias}, T)$ $F_{mag} \approx 0$	$k = k(H_{bias}, T)$ $F_{mag} \approx 0$	$k = k_{min}$ $F_{mag} > 0$

Modified tuning conditions for control in presence of magnetostrictive force.

control turned off



magnetostrictive force

$\Delta F_{\text{mag}} = -\theta \Delta i_c$

Young's modulus (left) & electromechanical coupling coefficient (right) of Terfenol-D transducer at different bias magnetic fields.

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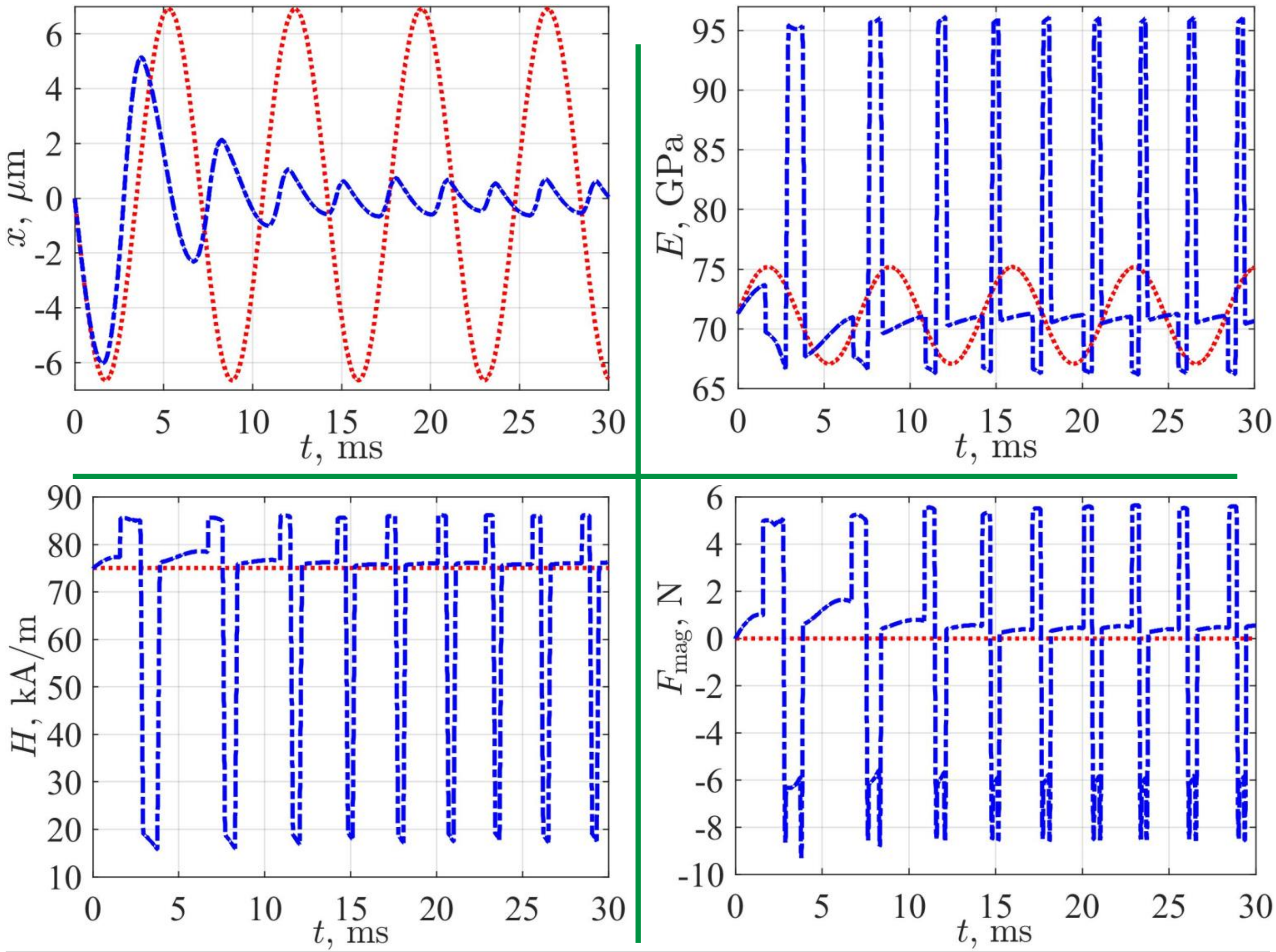
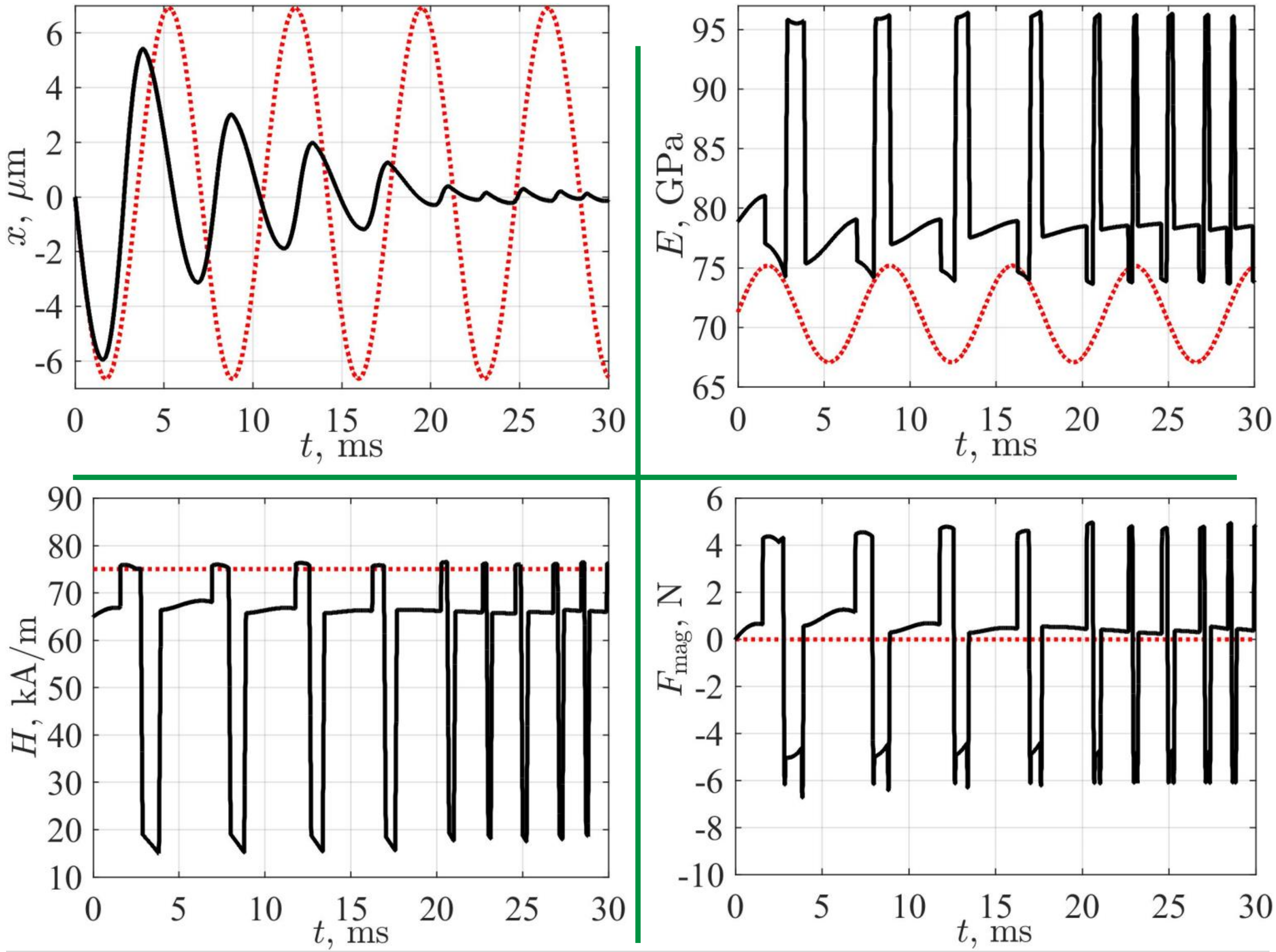
Voltage-controlled stiffness switching

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



Controlled response 1: uncontrolled (⋯⋯) and controlled (– · –).

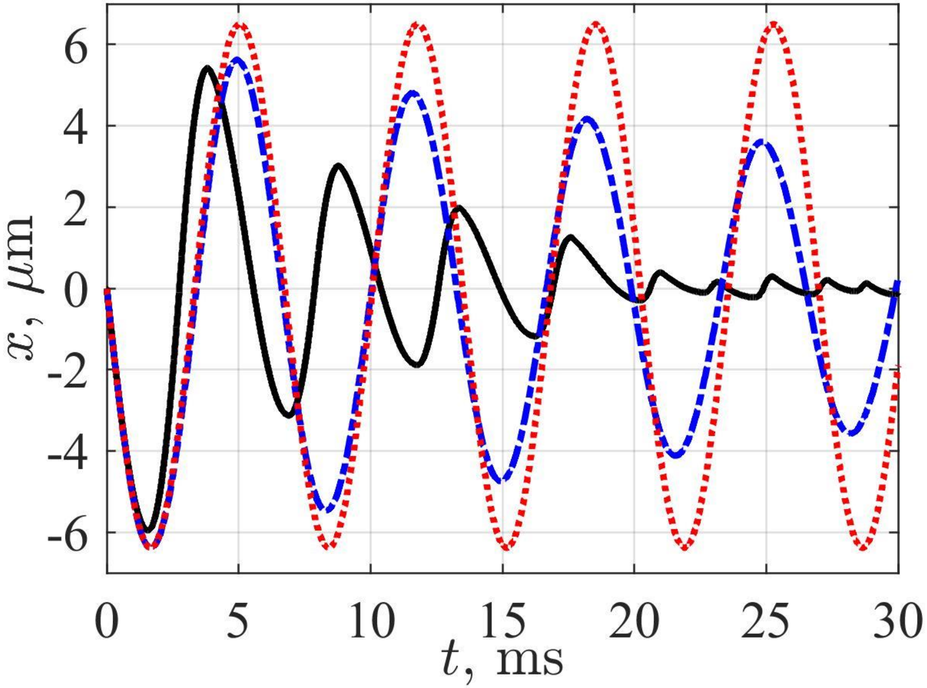
Voltage-controlled stiffness switching



Controlled response 2: uncontrolled (······) and controlled (——).

Voltage-controlled stiffness switching

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



Controlled response 2 with (——) and without (– · ·) F_{mag}.

	Effective Viscous Damping Factor
Controlled Response 1	0.25
Controlled Response 2	0.19
Controlled Response 2 (F_{mag} removed)	0.02

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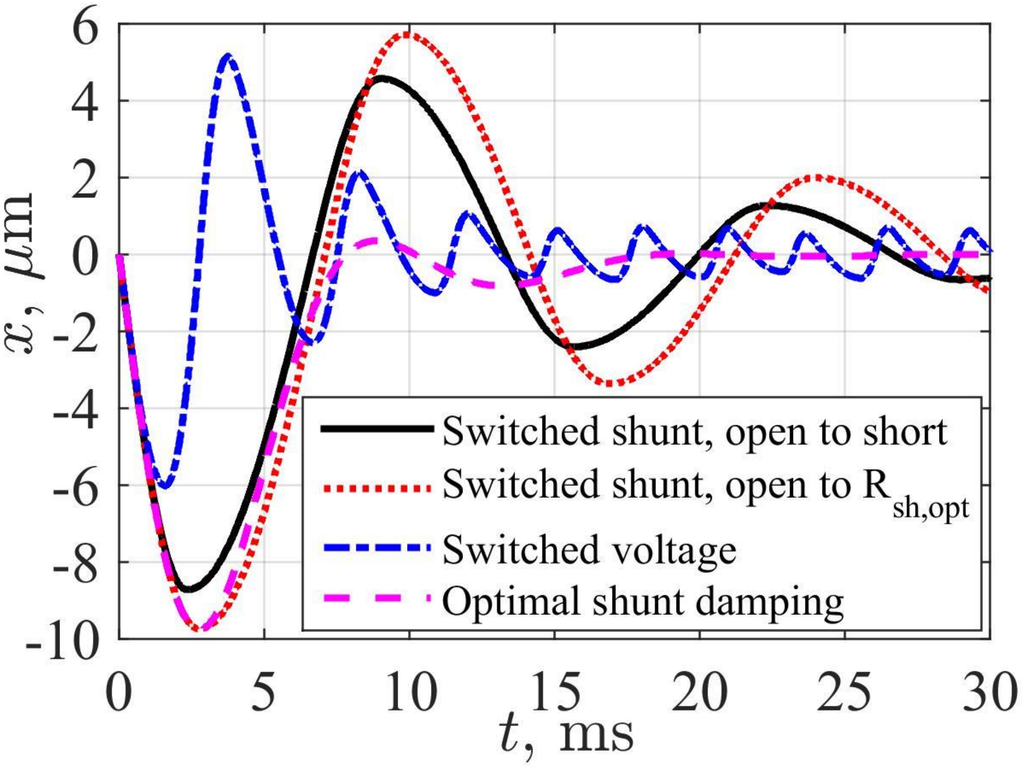
Comparison to shunting techniques

- 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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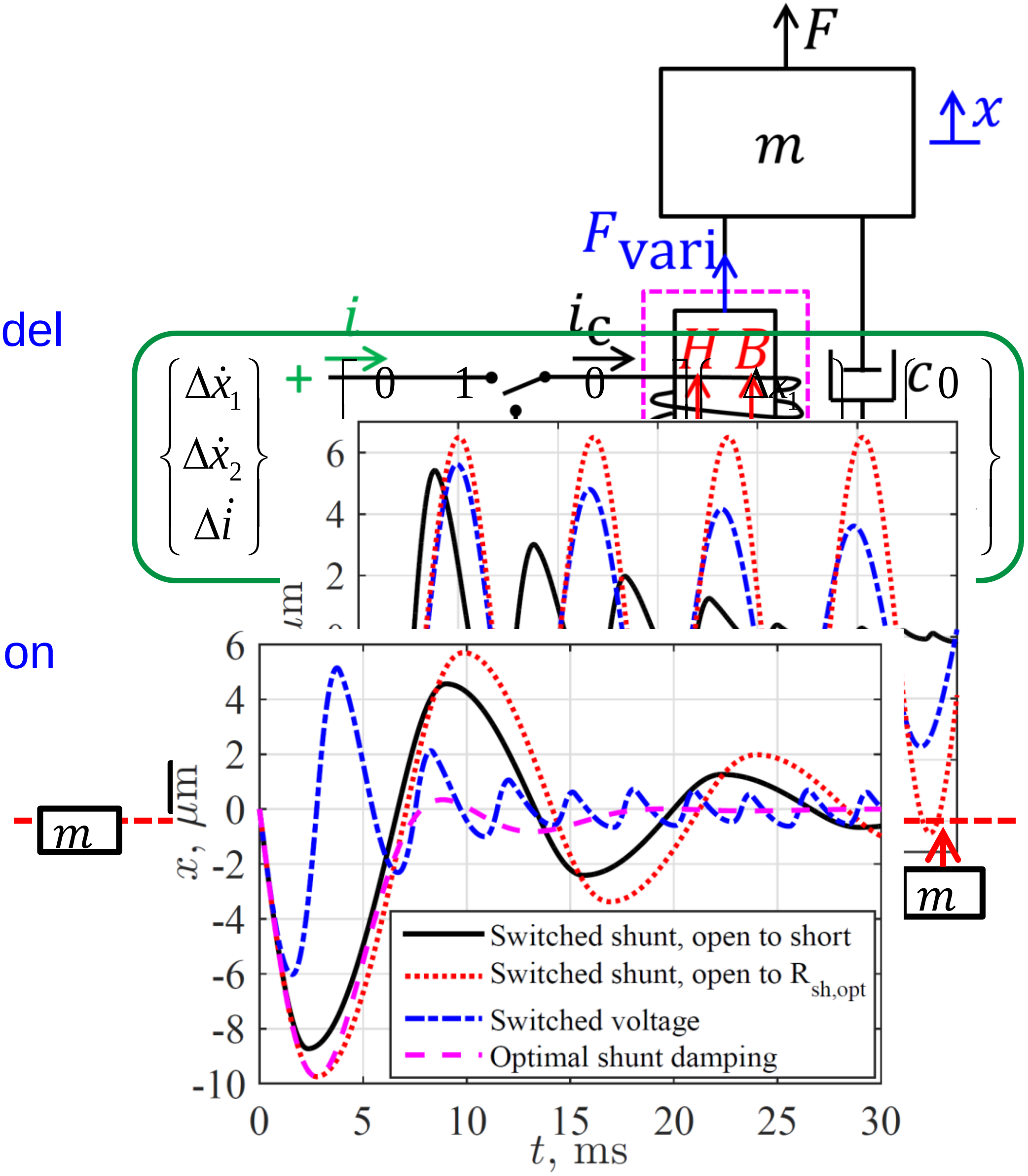
Summary

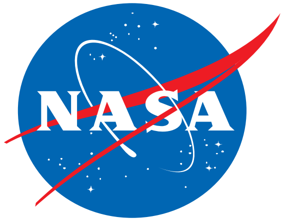
- Structural vibration control via stiffness switching of magnetostrictive transducers
- Nonlinear, electromechanical model developed
  - Voltage control of stiffness
  - Shunt control of stiffness
- Control of undamped, free vibration studied
- Modified control law developed
- Voltage-controlled switching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



Conclusions

	Voltage switching	Shunt switching
Modulus change	Large	Moderate
Need external power source?	Yes	No
Continuous stiffness tuning?	Yes	Yes
Unwanted magnetostrictive force?	Yes	No
Unwanted parametric force?	No	No (resistive shunts) Yes (reactive shunts)
Complexity	Moderate	Simple to moderate

- 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


NASA

Extra slides…..

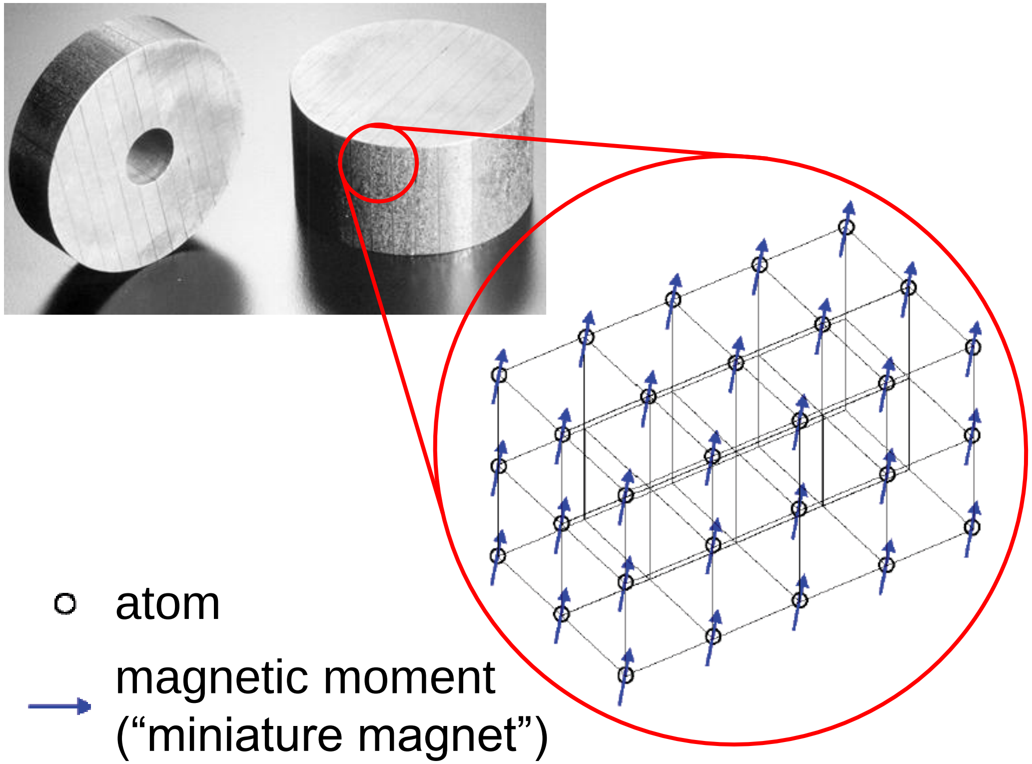
Magnetostrictive materials

- 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)

Magnetic: $\vec{\mathbf{B}} = \mu^{\mathrm{T}}\vec{\mathbf{H}} + \boxed{d\vec{\mathbf{T}}}$ **sensing**

Mechanical: $\vec{\mathbf{S}} = \boxed{d^{\mathrm{T}}\vec{\mathbf{H}}} + s^{\mathbf{H}}\vec{\mathbf{T}}$

actuation, λ



Stress $(\mathbf{T})$

Magnetic field $(\mathbf{H})$

		Piezoelectric	**Magnetostrictive** [4,5,27]		**Magnetorheological (MR) elastomer**
		PZT [1-3]	**Terfenol-D**	**Galfenol**	**MR rubber** [6,24-26]
Frequency bandwidth, Hz		≈1e6	≈1e4	≈2e3	>1.4e3
Modulus, GPa (tunable range)	Young’s	40–70	15–110	35–70	0.003–0.008
	Shear	–	–	–	0.005–0.008
Loss factor (max)		0.25	0.27	>0.13	>0.23
Tensile strength, MPa		40	40	350	6.5
Fatigue strength*, MPa		–	–	75	–
Energy conversion factor		0.48–0.78	0.7–0.8	0.6–0.7	–
Density, g/cm^3		4.7–7.8	9.25	7.8	≈2.8
Temp. limits, °C (lower/upper)		<-20 / 150–500	<-20 / 380	<-20 / 670	-51 / 121
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

* Fully reversed (R = -1)

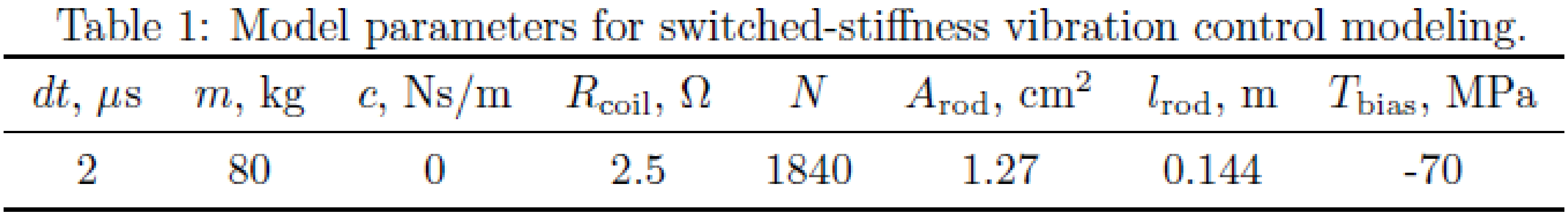
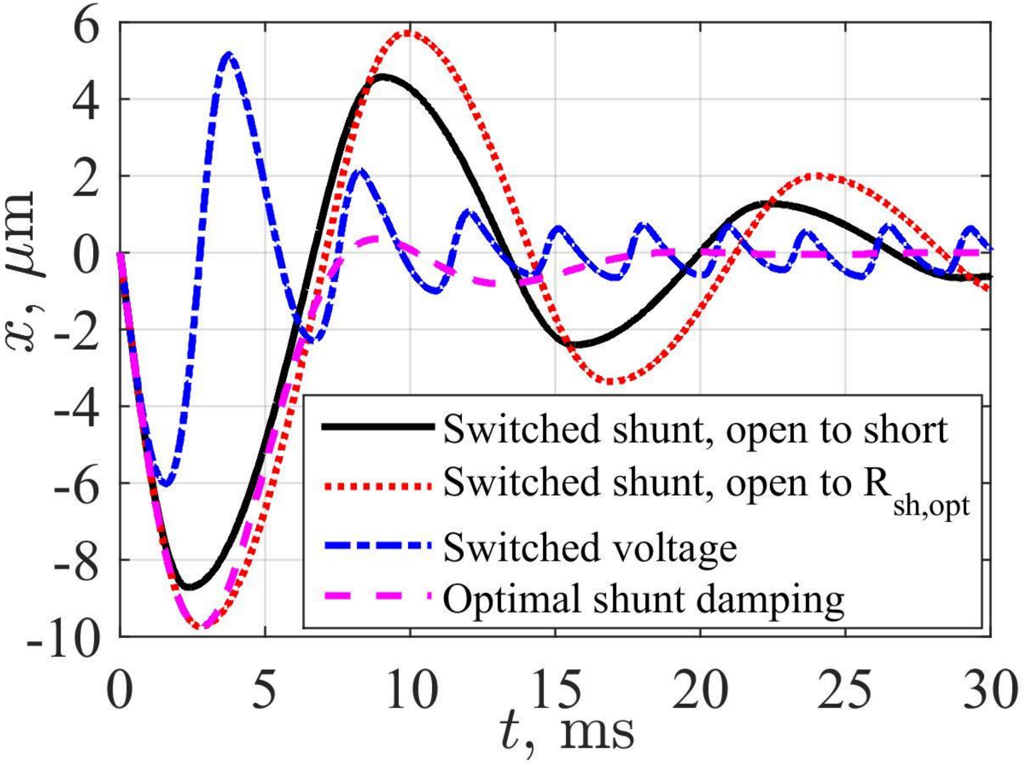


Table 1: Model parameters for switched-stiffness vibration control modeling.

dt, μs	m, kg	c, Ns/m	R_{coil}, Ω	N	A_{rod}, cm^2	l_{rod}, m	T_{bias}, MPa
2	80	0	2.5	1840	1.27	0.144	-70



	Effective Viscous Damping Factor
Switched voltage (controlled Response 1)	0.13
Switched shunt, open to short	0.20
Switched shunt, open to optimal resistance	0.17
Optimal resistive shunt damping	0.37

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 (μ^S)

Effective electrical impedance (for mass loading)

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

Current – Magnetic field relation

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

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

Magnetic field response

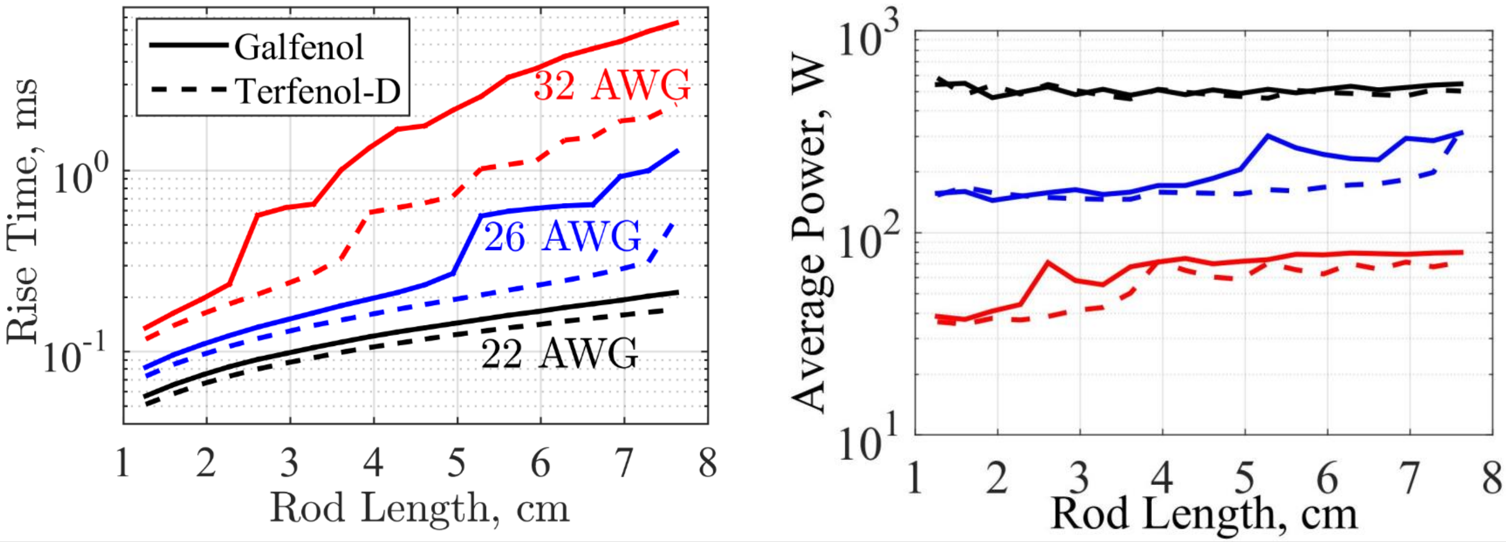
$$\boxed{H(s) = \frac{N}{l_{\text{coil}} Z_{\text{eff}}} V(s)}$$

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

Electromechanical transducer model (single-degree-of-freedom).

Magnetostrictive Variable-Stiffness Spring: Electromechanical modeling

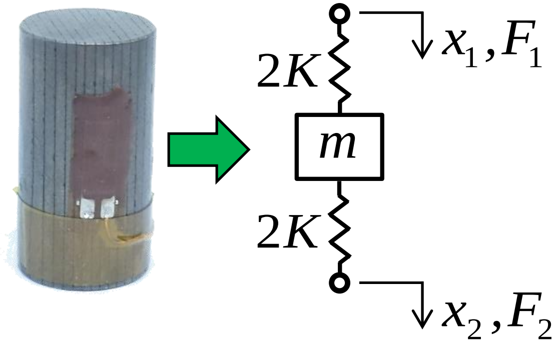
- Varispring operated about a large compressive bias
  - stiff when $H = 0$, softens as $H \to H_{\max}$
- Step change in field (stiffness) calculated as the response to step change in voltage
  - Galfenol or Terfenol-D, 3 electromagnet wire gauges
  - Minimum blocked inductance (minimum number of electromagnet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



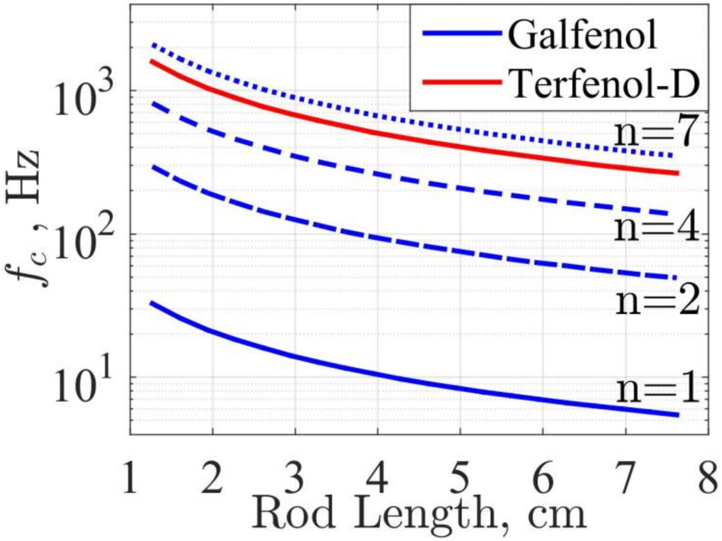
Rise time (left) and average power (right) required to reach tuning field with a 250 V step voltage; $m=2$ kg, equal modulus change

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



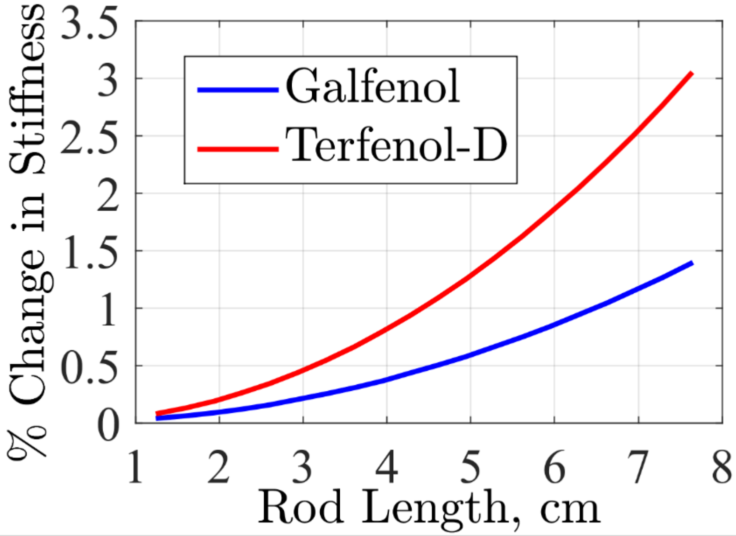
Lumped parameter model



Laminated rod

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

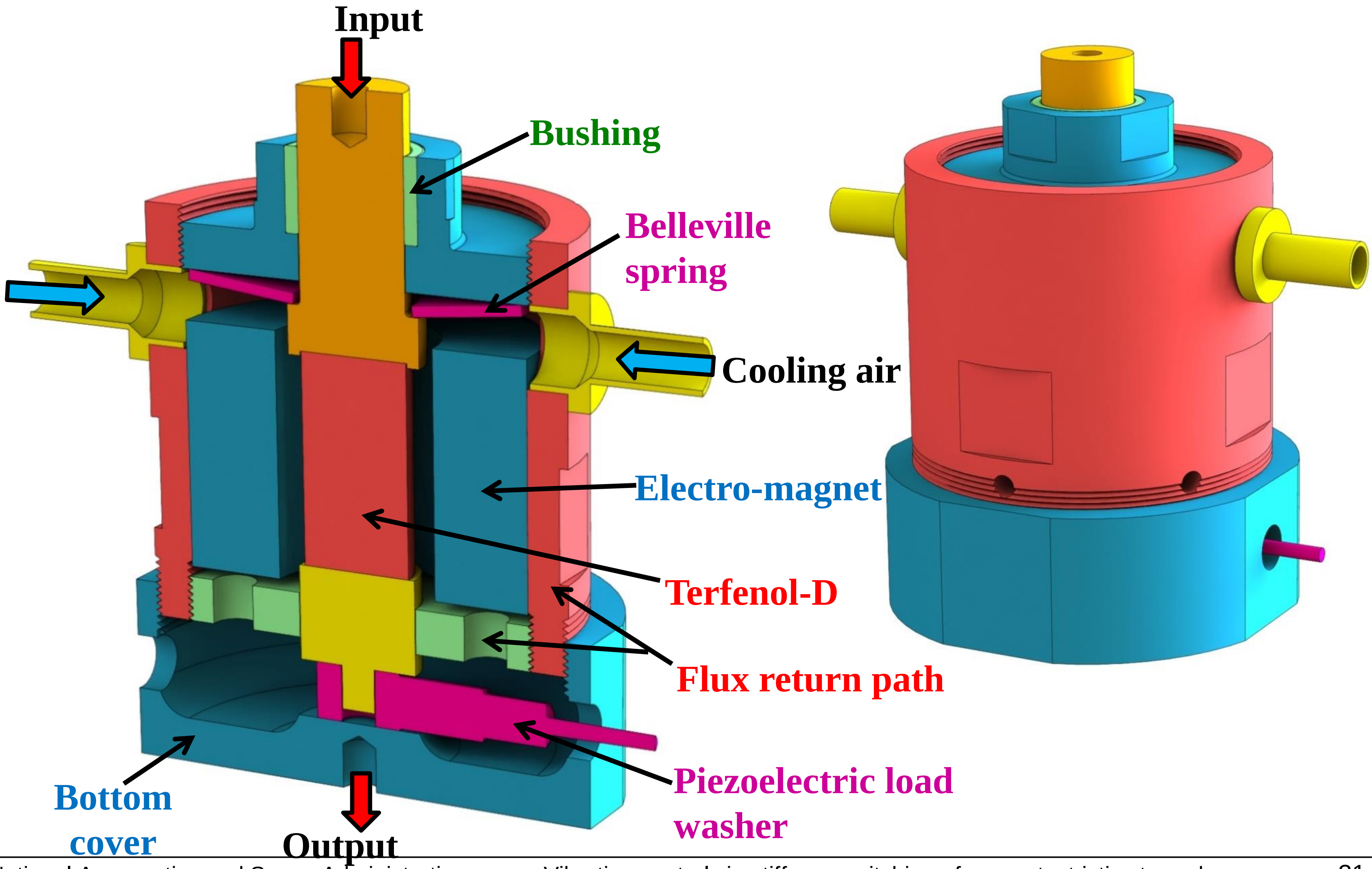
Magnetic diffusion cut-off frequency for solid and laminated rods.



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

Magnetostrictive Variable-Stiffness Spring: Design

- Terfenol-D selected for improved rise time, diffusion cut-off frequency, and static elastic modulus range



Input

Bushing

Belleville spring

Cooling air

Electro-magnet

Terfenol-D

Flux return path

Piezoelectric load washer

Bottom cover

Output

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