Shunted magnetostrictive devices in vibration control

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Abstract
Structural vibrations in rotating machinery may lead to imprecise motion control, excessive noise, or even structural damage. Magnetostrictive materials can dissipate unwanted vibrations via hysteresis, eddy currents, and joule heating while exhibiting an electrically-tunable elastic modulus. Harnessing this feature, this article presents a shunted magnetostrictive device that includes an iron-gallium (Galfenol) rod, a permanent magnet array, a flux return path, and shunt circuits. The stiffness tunability and damping of this passive device are measured under a 750 Hz sinusoidal axial compression for resistive, capacitive, and inductive shunt circuits. The effect of eddy currents stiffness and damping is investigated for the first time by comparing results from laminated and solid Galfenol rods. Solid Galfenol produces larger eddy current-based damping, while laminated Galfenol enables larger stiffness variation and total damping. This device demonstrates a power density of 19.83 mW cm\textsuperscript{-3} for vibration energy harvesting. The frequency-dependent behavior of the shunted device is tested from 5 Hz to 1 kHz for selected electrical loads.

Keywords: Galfenol, shunt damping, stiffness tuning, energy harvesting

(Some figures may appear in colour only in the online journal)

1. Introduction
Excessive vibrations in power transmission systems can cause negative effects, including detrimental noise, structure damage, or degraded motion control accuracy. The vibration response can be attenuated by tuning the system’s natural frequency or introducing structural damping. Stiffness tuning has been achieved passively by varying the pre-stress in a buckled system \cite{1}. However, continuous adjustment of pre-stress in real-time is inconvenient. Recent studies have implemented piezoelectric or electromagnetic transducers for active- or semi-active stiffness tuning \cite{2, 3} in which external power sources are required to drive the transducers. Davis and Lesieutre \cite{4} have experimentally validated a passive stiffness tuning device based on the Young’s modulus change in piezo ceramics. But its application in harsh loading conditions is hampered by the brittleness of piezo ceramics. Frequency tuning requires knowledge of the forcing frequency and targets few selected modes. Structural damping, however, can mitigate vibrations over a broad operating range. Global reductions to the aforementioned negative effects can be realized by attenuating the vibration at or near its source. Traditional methods based on fluids or viscoelastic materials introduce significant mass to the system and exhibit relatively low stiffness. If these materials are used in or near power transmission subsystems that require precise positioning (e.g. gearboxes, bearings, and antenna pointing drives), their low stiffness can compromise the alignment of components, which usually causes vibration to increase in spite of the added damping. Hence, controlling vibration at or near its source in power transmission systems requires vibration control devices that maintain the high stiffness of the system.
Magnetostrictive material such as terbium-iron-dysprosium alloys (Terfenol-D) and iron-gallium alloys (Galfenol) can provide natural frequency tuning and enhance structural damping while maintaining high stiffness in a solid-state package. Shunted magnetostrictive transducers, consisting of magnetostrictive materials, permanent magnets, and shunted circuits, have been developed as tunable springs and dampers in previous studies [5, 6]. The stiffness tuning of magnetostrictive materials originates from the stress- and magnetic-field-dependent Young’s modulus, also known as the ∆E effect. Magnetostrictive materials simultaneously experience elastic deformation S_e and magnetic-field-induced deformation λ under uniaxial loading. Magnetic-field-induced deformation, also known as magnetostriction, is caused by magnetic domain rotation and is a function of applied stress T and magnetic field H. As a result, the Young’s modulus E of magnetostrictive materials is

\[ E(H,T) = \frac{T}{S_e + \lambda(H,T)}. \]  

The ∆E effect has been experimentally characterized in the literature [7–10]. The permanent magnets in shunted magnetostrictive devices provide a constant magnetic flux bias. Due to the electro-magnetic coupling, the electric shunt connected to the magnetic circuit changes the magnetic flux distribution across the magnetostrictive materials and, therefore, enables passive tuning of the device’s stiffness.

The energy transformation, as presented in figure 1, allows for tunable damping in shunted magnetostrictive devices. Due to the unique magneto-mechanical coupling in magnetostrictive materials, mechanical energy is first converted to magnetic energy, which is dissipated via hysteresis and eddy currents. Following Faraday’s law, magnetic energy variation introduces an electrical potential across the shunted circuit, which induces additional energy dissipation through Joule heating. The hysteresis loss of magnetostrictive materials has been measured from monolithic elements [11–15], microscale thin films [16], and particulate composites [17]. Eddy current loss of magnetostrictive materials has been analyzed numerically [18, 19] and characterized experimentally [20, 21]. Recent studies demonstrated that the damping effect is related to the electrical impedance of the shunt circuit [5, 22, 23]. By replacing the shunted circuit with energy storage units, vibratory energy can be scavenged and utilized to power controllers or sensors [24]. Hence, shunted magnetostrictive devices can be self-sustained and multifunctional.

Due to its brittleness, Terfenol-D exhibits low reliability in shunted magnetostrictive devices [25]. Galfenol is mechanically-robust and can be conventionally machined into complex geometries. This study develops a shunted magnetostrictive device using either solid or laminated polycrystalline, <100>-oriented, highly-textured Fe_{81.4}Ga_{18.4} rods, and characterizes the device performance under axial mechanical excitation. This solid-state device can be installed at the vibration source to attenuate structural vibrations before they propagate throughout the system, thereby providing global vibration and noise reduction. The stiffness and damping tuning is contactless through electro-magnetic field interaction.

A shunted magnetostrictive device based on laminated Galfenol has been built and tested to experimentally validate a model [5]. However, the device underperformed due to the lack of magnetic flux path design. Further, only a limited set of data was presented; the influence of eddy currents and inductive shunt circuits has not been measured. To improve shunted magnetostrictive devices, this study re-designs the magnetic flux path, presents a complete characterization of the device’s impedance- and frequency-dependent responses for resistive, capacitive, and inductive shunts, and investigates the effect of eddy currents. Additional measurements are obtained to separate the mechanical energy dissipated through the device into its components: the energy loss in the magnetostrictive material, the coil, and the shunt circuit. This separation enables a deeper understanding of the device and a direct comparison of the measured trends to an existing model that neglects losses in the material. Moreover, this paper presents measurements of the electrical energy that can be harvested from the device.

Device configuration and experimental setup are explained in section 2. Performance metrics describing the damping effect, the stiffness variation, and the energy conversion capability are summarized in section 3. In section 4, the performance of the shunted magnetostrictive device is characterized. Measurements are made under various resistive, capacitive, and inductive loads at 750 Hz. The frequency-dependent behavior at selected load impedance is then measured up to 1 kHz. Finally, the influence of mechanically-induced eddy
The magnetic permeability of Galfenol is much higher than that of the low carbon steel ring. To ensure concentric alignment, a 3D-printed plastic ring is placed between the magnetic holder and the steel ring. Compared to the device configuration, the plastic ring is utilized to hold 24 Alnico magnets and iron powder plates. The magnetic force measured due to the attraction between the permanent magnets and iron powder plates can be controlled. An iron powder core (Fe-Si, 1.67 T saturation, relative magnetic permeability of 60) is placed on each end of the shunted magnetostrictive device to form a closed magnetic flux path to prevent eddy currents in the surrounding components (e.g., top target, probe holder).

Figure 2. (a) Physical assembly and (b) schematic of the shunted magnetostrictive device based on Galfenol.
from the device containing a solid and laminated Galfenol rod are 14.19 N and 13.97 N, respectively. The magnetic force is added to the load cell measurement following reference [26]. Any mass in between the rod and load cell cause errors in the force measurement due to inertial force [20]. The error in the dynamic force due to inertial forces is less than 0.6% at 1 kHz. The deformation of the Galfenol rod is measured by a pair of precision capacitive displacement probes, which are held by a U-shaped aluminum part. Each displacement probe provides a range of ±100 microns with accuracy of better than 0.1%. The average power and power density require precise measurement of voltage across the pickup coil $V_L$. The influence of the data acquisition system, filters, and connection cables on the voltage measurement has been calibrated and compensated numerically in data post-processing. Finite element simulation in a commercial multiphysics software confirms that the first vibration mode of the physical assembly depicted in figure 3(b) occurs at 4093 Hz, which is much higher than the testing frequencies.

3. Performance metrics

In this study, the vibration force has a frequency of 750 Hz, which is the fundamental gear mesh frequency of a particular helicopter gearbox. The force amplitude is similar to the values used for previous shunted piezoelectric devices to permit a direct comparison [6]. The research objective is to maximize the shunted magnetostrictive device’s stiffness variation and energy dissipation capacity under the given vibration source (i.e., its potential for controlling vibration at the source in power transmission systems).

The stiffness of the magnetostrictive device is treated in the same manner as an elastomeric material. Following the Fast Fourier Transform (FFT) method in ASTM D5992-96(2011) [28], the device’s stiffness $K^*$ is a complex valued stiffness calculated as

$$K^* = \frac{F^*}{S^*} = K(1 + j\eta_0),$$

(2)

where $K$ is the lossless stiffness, $\eta_0$ is the total loss factor of the system, $j = \sqrt{-1}$, $F^*$ and $S^*$ are the fundamental harmonics (at excitation frequency $f_0$) in force and displacement, respectively. Values of $K$ and $\eta_0$ are directly extracted from the force-displacement measurements. The value of $K$ has a range from $K_{\text{min}}$ to $K_{\text{max}}$. To quantify the stiffness tunability of the shunted magnetostrictive device, a normalized stiffness variation $\bar{K}$, which is a function of $Z_L$ and $f_0$, is defined as

$$\bar{K} = \frac{K_{\text{max}} - K_{\text{min}}}{K_{\text{max}}}. \quad (3)$$

The total loss factor $\eta_0$ is a ratio of the total energy dissipated per radian of the vibration cycle to the stored energy (kinetic plus potential) associated with vibration ($E_{\text{osc}}$) [29]. The total loss factor is decomposed into the loss factors due to the rod (material hysteresis and eddy current loss) $\eta_{\text{device}}$, the electrical shunt $\eta_{\text{shunt}}$, and the pickup coil $\eta_{\text{coil}}$, by separating the total energy dissipated into the energy dissipated in the rod, shunt ($E_{\text{shunt}}$), and coil ($E_{\text{coil}}$), respectively. Hence,

$$\eta_0 = \eta_{\text{device}} + \eta_{\text{shunt}} + \eta_{\text{coil}}.$$

The value of $\eta_{\text{shunt}}$ is calculated as [29]

$$\eta_{\text{shunt}} = \frac{E_{\text{shunt}}}{2\pi E_{\text{osc}}}. \quad (4)$$
Here, the oscillation energy is

\[ E_{osc} = \frac{1}{2} K |S|^2. \]  

(5)

The energy dissipated in the electrical circuit \( E_{\text{shunt}} \) is [6]

\[ E_{\text{shunt}} = \frac{1}{2} \frac{|V|^2}{Z_L} \Re (Z_L), \]  

(6)

where \( V \) is the fundamental harmonic of \( V(t) \) at \( f_0 \). For a coil resistance \( R_c \), the energy dissipated in the coil is

\[ E_{\text{coil}} = \frac{1}{2} \frac{|V|^2}{Z_L} R_c. \]  

(7)

Following the definition of loss factor, the value of \( \eta_{\text{coil}} \) is

\[ \eta_{\text{coil}} = \frac{E_{\text{coil}}}{2\pi F} R_c. \]  

(8)

The value of \( \eta_{\text{device}} \) is thus calculated as

\[ \eta_{\text{device}} = \eta_0 - \eta_{\text{coil}} - \eta_{\text{shunt}}. \]  

(9)

The electrical energy dissipated by the resistive load \( R_L \) is approximately equal to the useful electrical energy that can be scavenged. Hence, the energy harvesting capability, which is described by the average power output \( \bar{P} \), is characterized as [24]

\[ \bar{P} = \frac{1}{2} \frac{|V|^2}{R_L} R_L. \]  

(10)

To eliminate the influence of the device’s volume, an average power density \( \bar{D} \) is defined as [24]

\[ \bar{D} = \frac{P}{V_G}, \]  

(11)

where \( V_G \) is the volume of the Galfenol rod.

4. Experimental results

Scheidler and Asnani [5] have theoretically proved that the normalized stiffness variation \( K \) and loss factor \( \eta_0 \) of shunted magnetostrictive devices are simultaneously maximized when maximizing the coupling factor, which is determined by the interplay of magnetic field bias \( H_0 \) and mechanical compression bias \( F_0 \). For a shunted magnetostrictive device excited by a given dynamic force, the optimal values of \( H_0 \) and \( F_0 \) will maximize the open circuit voltage across the coil. The value of \( H_0 \) is fixed and relies on the permanent magnet configuration, which has been explained in section 2. A constant force \( F_0 \) is applied to the shunted device on top of a 750 Hz and 73.51 N amplitude sinusoidal compression. The value of \( F_0 \) is gradually increased until the resulting open circuit voltage peaks. Following this approach, the bias compression \( F_0 \) for the laminated and solid Galfenol rods is determined to be 746 N and 604 N, respectively. The non-magnetically-conductive adhesive layers in the laminated sample reduce its effective magnetic permeability and result in increased \( H_0 \). Hence, a larger \( F_0 \) is required to balance the larger \( H_0 \) for the laminated Galfenol sample.

This study first investigates the stiffness variation and damping of the shunted magnetostrictive device based on laminated Galfenol and using resistive, capacitive, or inductive shunts. A 750 Hz sinusoidal compression is selected as the mechanical excitation. For selected resistive and capacitive shunts, the rate-dependent performance of the shunted device is investigated between 5 Hz and 1 kHz. Due to the non-linearity in material properties and control inaccuracy, the actual applied force consists of the fundamental component as well as unavoidable higher harmonics. The unwanted 2nd harmonics have a magnitude of \( \leq 4.2\% \) relative to the desired stress sinusoid within the aforementioned frequency range. The unwanted 3rd harmonics typically have a magnitude of \( \leq 4.9\% \) relative to the desired stress sinusoid except for a narrow frequency range from 372 Hz to 398 Hz, where the 3rd harmonics have a magnitude of \( \leq 13.5\% \). To quantify the influence of eddy currents, the tests are repeated for the shunted device based on solid Galfenol. A test without the electrical shunt is also completed to quantify the damping introduced by the eddy current loss alone.

4.1. Laminated Galfenol - Impedance sweep

4.1.1. Resistive sweep. A 750 Hz, 73.51 N amplitude sinusoidal force \( F_d \), together with an DC force \( F_0 = 746 \) N, is applied on the laminated Galfenol rod. The corresponding loss factor \( \eta_0 \) and stiffness \( K \) are measured under different resistive loads \( R_L \). Figure 4(a) shows the bell-shaped loss factor \( \eta_0 \) as \( R_L \) increases from short circuit to open circuit. This trend mirrors the trend predicted by the quasi-linear model in reference [5]. The loss factor \( \eta_0 \) reaches the maximum value of 0.061 when \( R_L = 138.2 \) Ω. When the pickup coil is shorted or open, the energy loss on the shunt circuit is negligible and \( \eta_0 = \eta_{\text{device}} = 0.009 \). Due to the negligible eddy currents in the laminated Galfenol rod, \( \eta_{\text{device}} \) is mainly introduced by material hysteresis. The electrical shunt accounts for more of the loss factor than the pickup coil, except for resistance less than about 8 Ω.

Figure 4(b) shows that the stiffness \( K \) of the laminated Galfenol rod decreases monotonically from 74.9 N/μm to 66.7 N/μm as \( R_L \) increases, which corresponds to a \( K \) of 11.0%. This observation matches previous quasi-static measurements [30]. According to the Stoner-Wohlfarth approximation, bulk magnetostrictive materials are composed of non-interacting magnetic domains. An external magnetic field rotates the magnetic domains, causes macroscopic deformation, or magnetostriction, and varies the material’s stiffness. In a shunted magnetostrictive device, the induced current in the pickup coil generates an additional magnetic field \( H_d \) on top of the bias field that is provided by permanent magnets. Under resistive loading, \( H_d \) prevents magnetic domain rotation, reduces magnetostriction, and correspondingly increases
Figure 4. (a) Loss factor, (b) stiffness, and (c) energy harvesting capacity measured from the shunted device based on the laminated Galfenol and resistive load.

Figure 5. (a) Loss factor and (b) stiffness from the shunted device based on the laminated Galfenol and capacitive load.

the stiffness of the Galfenol rod. When the coil is shorted, the induced current and $H_d$ are maximized and accordingly the stiffness. This trend also mirrors that was predicted in reference [5].

The maximum $P$ and $D$ are 5.61 mW and 19.83 mW cm$^{-3}$, respectively, when $R_L = 138.2 \ \Omega$. The amount of electrical energy scavenged from the system is large enough to power micro-controllers and sensors. Hence, future dampers or isolators based on a shunted magnetostrictive device can be simultaneously adaptive and self-sustainable. However, the energy harvesting capability is lower than that of similar shunted piezoelectric devices, since the coil dissipates considerable amount of electrical energy.

4.1.2. Capacitive sweep. Magneto-electric coupling can be further amplified in the shunt circuit by complementing the coil’s inductance with a capacitive shunt to create a resonant response. The same sinusoidal force $F_d$ together with static force $F_0$ are applied on the laminated Galfenol rod for different capacitive loads $C_L$. A maximum loss factor $\eta_0 = 1.34$ is obtained when $C_L = 1.44 \ \mu F$ and an electrical resonance is created, as shown in figure 5(a). The maximum $\eta_{\text{shunt}}$ and $\eta_{\text{device}}$, which are also observed at $C_L = 1.44 \ \mu F$, are 0.33 and 1.01, respectively. Figure 5(b) shows a large discontinuity in stiffness around the resonance. As $C_L$ increases from 1.26 $\mu F$ to 1.94 $\mu F$, the stiffness $K$ increases from 38.9 N/µm to 99.4 N/µm corresponding to a $K$ value of 60.9%. The stiffness drops below the open circuit value and increases above the short circuit value around the electrical resonance.

4.1.3. Inductive. The shunted magnetostrictive device is tested for different inductive loadings under the same sinusoidal force $F_d$ and static force $F_0$. As shown in figure 6(a), the inherent resistance of the inductor coils create small but appreciable loss factors, which needs to be considered for improving the accuracy of the quasi-linear model [5]. When $L_L$ is smaller than 1 mH, the measurement is similar to the shorted condition shown in figure 4. Due to energy loss on $R_c$, the loss factor $\eta_{\text{shunt}} = 0.004$ when $L_L = 0.1 \ \text{mH}$. When $L_L$ is large ($> 0.1 \ \text{H}$), the electrical impedance is relatively high and the system response is similar to the open-circuit results shown in figure 4. For instance, the loss factor at $L_L = 11.11 \ \text{H}$ is 0.009, which is primarily due to the material’s hysteresis. The stiffness variation is also similar to that of the resistive shunt. The stiffness $K$ decreases from 75.2 N/µm to 67.0 N/µm when $L_L$ increases from 0.1 mH to 11.11 H. Compared to the results of the resistive load sweep, varying the inductive load provides...
Figure 6. (a) Loss factor and (b) stiffness from the shunted device based on the laminated Galfenol rod and inductive load.

Figure 7. (a) Loss factor, (b) stiffness, and (c) energy harvesting capacity measured from the shunted device based on laminated Galfenol for an excitation frequency between 5 Hz and 1 kHz \((R_L = 138.2 \, \Omega)\).

A similar \(\bar{K}\) value without significantly changing the system’s damping effect.

4.2. Laminated Galfenol - Frequency sweep

4.2.1. Resistive. A 78.51 N amplitude sinusoidal force \(F_d\) superimposed on the selected bias force \(F_0 = 746\, N\) is applied on the laminated Galfenol rod. The resistive load connected to the pickup coil is \(R_L = 138.2\, \Omega\). The excitation frequency \(f_0\) of \(F_d\) changes from 5 Hz to 1000 Hz. The rate-dependent loss factor and stiffness are presented in figure 7.

The material hysteresis loss per vibration cycle, which is due to pinning site loss, is frequency independent \([21, 32]\). The value of \(\eta_0\) increases from 0.004 to 0.064 as \(f_0\) varies from 5 Hz to 1000 Hz. The value of \(\eta_{shunt}\) initially increases with respect to the excitation frequency. Eddy currents induce magnetic field diffusion in a magnetostrictive rod, thereby reducing magnetic flux density variation and, thus, the voltage across the shunt \([18, 31]\). The loss factor \(\eta_{shunt}\) starts to decline around 750 Hz, since the resistant shunt is tuned to peak at 750 Hz. A slightly negative \(\eta_{device}\) is observed between 38 Hz and 195 Hz. This measurement error is likely due to a small inaccuracy in the phase calibration procedure for the displacement probes, leading to an over-compensation of the phase lag introduced by the sensor and its conditioning electronics over this frequency range. Figure 7(b) shows that the stiffness of the laminated Galfenol rod slightly drops around 200 Hz and then increases. The initial drop in stiffness is still under investigation. The stiffness increment after 200 Hz is induced by the increasing current in the shunt circuit and an increase in eddy currents. The large induced current through the coil generates an additional magnetic field \(H_d\) which prevents domain rotation, thus increasing system stiffness. The loss factor \(\eta_{device}\) due to material hysteresis and eddy currents is

\[
\eta_{device} = \frac{E_{device}}{2\pi F_{osc} K} = \frac{E_{device} K}{\pi |F^*|^2}.
\]  

(12)

For the laminated Galfenol rod, \(E_{device}\) mainly includes the material’s hysteresis loss, which is independent of \(f_0\). The force amplitude \(|F^*|\) is held constant. Hence, the trend of \(\eta_{device}\) follows the trend of \(K\), as shown in figure 7.

Figure 7(c) presents the average power and power density available from the laminated Galfenol rod for different excitation frequencies. As \(f_0\) increases from 5 Hz to 1 kHz, \(P\) monotonically increases from 0.58 \(\mu W\) to 6.85 mW while \(D\) monotonically increases from 2.04 \(\mu W/cm^3\) to 6.85 mW cm\(^{-3}\).
Comparing the loss factor measurements of the device based on laminated Galfenol shown in figure 4(a), the trend of $\eta_{\text{device}}$ is different due to the interplay of the induced current in the pickup coil and the eddy current in the solid rod. The value of $\eta_{\text{device}}$ consists of material hysteresis and eddy current loss in the solid Galfenol rod. When the pickup coil is shorted, the induced current is maximized, and it creates an additional magnetic field that counteracts the magnetic bias and eventually suppresses the eddy currents. Hence, $\eta_{\text{device}}$ is dominated by the material’s hysteresis and reaches the minimum of 0.012, which, as expected, is very similar to the 0.009 minimum observed for the laminated rod. As the load impedance increases, the induced current in the coil reduces and thus the influence of eddy current becomes significant. When the pickup coil is open, the eddy current loss is maximized. According to figure 4(a), the material hysteresis peaks when the load impedance matches $R_{\text{opt}}$ in reference [5]. Due to the combined effect of material hysteresis and eddy current loss, $\eta_{\text{device}}$ reaches a maximum value of 0.035 when $R_L = 354.2 \, \Omega$. The trend of $\eta_{\text{shunt}}$ is similar to the measurement from the device based on laminated Galfenol. The peak value of $\eta_{\text{shunt}}$ (0.015 at $R_L = 97.2 \, \Omega$) is less than half of that observed from the laminated rod, since the eddy currents create magnetic field diffusion that reduces the magneto-mechanical coupling.
4.3.2. Capacitive sweep. As with the shunted device based on laminated Galfenol, the loss factor can be significantly improved by attaching a capacitor to the pickup coil to maximize the magneto-electric coupling over a narrow frequency bandwidth, as shown in figure 10(a). The same dynamic force $F_d$ and the selected bias force $F_0$ are applied on the shunted device based on solid Galfenol. The maximum $\eta_0$ and $\eta_{\text{shunt}}$ are 0.219 and 0.017, respectively, when $C_L = 1.44 \, \mu F$. The bounds of the $\eta_{\text{device}}$ response (0.033 at minimal capacitance and 0.012 at maximal capacitance) are respectively equal to the open and short circuit $\eta_{\text{device}}$ from the resistance sweep test. Figure 10(b) shows that the stiffness increases from 59.5 N/µm to 72.5 N/µm as $C_L$ increases from 1.22 µF to 2.91 µF. This corresponds to a $K$ of 17.9%. Compared to the results from the shunted device based on laminated Galfenol, the damping effect and stiffness variation are much smaller due to increased eddy currents in the device based on solid Galfenol.

4.3.3. Inductive sweep. Figure 11 presents the loss factor and stiffness measurement for various inductive loads under the same dynamic and static force. When $L_d = 0.1 \, mH$ and the electrical impedance is low, the loss factor $\eta_0 = 0.014$ is similar to the shorted condition. When $L_d = 11.11 \, H$ and the electrical impedance is high, the loss factor $\eta_0 = 0.033$ is the same as the open circuit value observed in the resistive sweep. Due to the additional energy loss introduced by eddy currents, the loss factor variation is larger than that observed from the shunted device based on laminated Galfenol, shown in figure 6(a). The stiffness $K$ decreases from 67.1 N/µm to 62.6 N/µm monotonically as $L_d$ changes from 0.1 mH to 11.11 H. The normalized stiffness variation is 6.7%, which equals the value achieved from the resistive sweep, but is much less than the value obtained from the shunted device based on laminated Galfenol.

4.4. Solid Galfenol - Frequency sweep

4.4.1. Resistive. In this test, a sinusoidal force $F_d$ with an amplitude of 73.51 N superimposed on the selected bias force $F_0 = 604$ N is applied on the shunted device based on solid Galfenol. The resistive load that maximizes the loss factor $\eta_0 (R_L = 115.2 \, \Omega)$ is connected to the pickup coil. The excitation frequency $f_0$ varies from 5 Hz to 1000 Hz. The rate-dependent loss factor and stiffness are presented in figure 12.

The value of $\eta_{\text{shunt}}$ initially increases with increasing $f_0$. As $f_0$ exceeds a certain value, the eddy currents dominate, thus reducing magneto-mechanical coupling in the pickup coil. Hence, a maximum $\eta_{\text{shunt}} = 0.013$ is observed at 541 Hz. According to equation (12), the trend of $\eta_{\text{device}}$ follows the trend of $K$. The initial drop in $K$ around 200 Hz, which is
also observed from the shunted device based on laminated Galfenol, is under investigation. At high frequencies, large induced current in the coil and eddy currents suppress magnetic moment rotation. As a result, the system’s stiffness increases above 200 Hz. Compared to the loss factor measurement presented in figure 7(a), the value of $\eta_0$ from the shunted device based on solid Galfenol is larger than that from the laminated device below 300 Hz. Beyond 300 Hz, $\eta_0$ from the shunted device based on laminated Galfenol is larger. This indicates that the eddy current loss or the laminations are beneficial to create more system damping when there is small to moderate excitation frequency.

The average power and average power density measured from the shunted device based on solid Galfenol are presented in figure 12(c) as a function of excitation frequency $f_0$. As $f_0$ is increased from 5 Hz to 1 kHz, $P$ increases from 0.38 $\mu$W to 2.67 mW and $D$ increases from 1.33 $\mu$W/cm$^3$ to 9.45 mW cm$^{-3}$. The power generated from the shunted device based on solid Galfenol is less than that from laminated Galfenol over the entire frequency range.

4.4.2. Capacitive. The same dynamic force $F_0$ with a varying frequency $f_0$ is applied on the solid Galfenol rod when a capacitive load $C_L = 1.74$ $\mu$F is attached to the pickup coil. Due to the electrical resonance, a peak of $\eta_0 = 0.219$ is achieved at 750 Hz, as shown in figure 13(a). The value of $\eta_0$ drops quickly when $f_0$ shifts away from resonance. Figure 13(b) shows that stiffness of the solid Galfenol rod varies from 58.3 N/$\mu$m to 73.3 N/$\mu$m, or by 20.5%, when the excitation frequency $f_0$ increases from 593 Hz to 945 Hz. The solid Galfenol rod exhibits a relatively small damping effect, as well as stiffness variation around the electrical resonance.

4.5. Solid Galfenol - Eddy current effect

Deng and Dapino [19] have recently designed a Galfenol-based and coil-less damper that takes advantage of stress-induced eddy current loss and material hysteresis alone. This damper concept is tested experimentally in this study by disconnecting the electrical shunt from the coil shown in figure 3(a). A dynamic force with an amplitude of 73.51 N and a variable frequency of $f_0$ together with two different bias forces is applied to the shunted device based on solid Galfenol. The corresponding loss factors and stiffness are presented in figure 14. When a large compression force $F_0 = 2364$ N is applied, the Galfenol rod is mechanically saturated. In this saturation state, magnetic domains are oriented in the plane that is perpendicular to $F_0$ and no magneto-mechanical coupling exists. Hence, the loss factor is negligible and the stiffness...
Figure 13. (a) Loss factor and (b) stiffness of the solid Galfenol rod at $C_L = 1.74 \, \mu F$, when excitation frequency increases from 5 Hz to 1 kHz.

Figure 14. (a) Loss factor and (b) stiffness from the shunted device based on solid Galfenol from an excitation frequency between 5 Hz and 1 kHz (open circuit shunt).

5. Discussion

The stiffness of the shunted magnetostrictive device is a function of the shunt’s electrical impedance, as shown in table 1. The maximum loss factor and the associated frequency bandwidth are presented in table 2. The device presented in this study exhibits much higher loss factors and stiffness variations compared to the one presented in reference [5] due to the enhanced magneto-mechanical coupling enabled by the additional magnetic flux path. The improved performance will facilitate more effective vibration control with no change in the device’s form factor and a minimal increase in its mass. Key observations include:

- Resistive load - the loss factor $\eta_0$ is maximized when the resistive load matches the optimal resistance in reference [5]; the stiffness $K$ decreases monotonically as the load’s resistance increases.
By comparing measurements from laminated Galfenol- and solid Galfenol-based shunted devices, the effect of eddy currents on shunted magnetostrictive devices has been studied and the key observations include:

- **Stiffness tuning** - the stress-induced eddy currents prevent magnetic moment rotation and decrease magnetostriction. Thus, eddy currents reduce $K$ for each type of electrical shunt.
- **Damping** - stronger eddy currents increase the loss in the magnetostrictive element, but were found to reduce the total loss of the device due to a reduction in the magneto-electric coupling. As a result, devices containing laminated rods provide higher total damping capability than those containing solid rods.
- **Energy harvesting** - the eddy currents induce magnetic field diffusion, limit magnetic flux density variation, and reduce the electrical power produced by the shunted magnetostrictive device. Hence, eddy currents are detrimental to energy generation over the entire frequency range.

Lastly, this study considered a simplified vibration control device that is similar to the shunted magnetostrictive device without the coil or shunt circuit. This device is simpler and potentially more compact than the shunted magnetostrictive device and can be directly integrated into structures. This device can be adaptive via pre-load. It exhibits a loss factor ranging from 0.003 to 0.043 and $K$ of 19.3% at 1 kHz as the bias compression changes from 604 N to 2364 N.

### 6. Concluding remarks

This study presents an experimental characterization of a shunted magnetostrictive device for vibration control applications. The device consists of a magnetostrictive rod (solid or laminated, <100>−oriented, highly-textured, polycrystalline Fe$_81$Ga$_18$, a coil, a permanent magnet array, a flux return path, and a shunt circuit. Because of the unique $\Delta E$ effect of magnetostrictive materials, the stiffness of this device can be continuously tuned in real-time by varying the shunt’s electrical impedance. An inductive shunt can be used to create a moderate change in stiffness (up to 11%) without appreciably affecting the damping. By utilizing a variable shunt capacitance, the device can be used to create a variable mechanical notch filter.

This device can also attenuate unwanted structural vibrations due to its magneto-electric coupling and the magnetostrictive element’s material hysteresis and eddy current loss. The loss factor of the system can also be tuned by varying the shunt’s electrical impedance. Shunted magnetostrictive devices can provide moderate damping (loss factor > 0.06) over a relatively broad frequency range via resistive shunts and very high damping (loss factor > 1.3) over a narrow band via capacitive shunts.

Unlike most vibration damping solutions, this device is mechanically stiff and has no moving parts. Therefore, it can be designed to be an integral part of the structure. By attaching...
the electric circuit to an energy harvesting and storage unit, this device can scavenge useful electricity from ambient vibrations. Therefore, the stiffness and damping tuning can potentially be self-powered.

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