# High Bandwidth Tunability in a Smart Vibration Absorber

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**ABSTRACT:** An electrically tunable vibration absorber based on the strong $\Delta E$ effect of Terfenol-D has been developed. A general description of tuned vibration absorbers is presented along with a description of the magnetostrictive effects that make an electrically tunable Terfenol-D vibration aborber function. It is emphasized that the large modulus changes achievable with the proposed magnetostrictive vibration absorber arise as a consequence of the stiffening of the crystal lattice as the magnetic field is increased from the demagnetized state to magnetic saturation. This is in contrast to the small modulus changes often reported in the literature which are achieved by operating smart materials between their open- and short-circuit states. Experimental results are presented that show agreement with prior art and demonstrate control of a magnetostrictive actuator resonant frequency between 1375 Hz and 2010 Hz by electrically varying the elastic modulus of a magnetostrictive material. This operating principle is then implemented to obtain high bandwidth tunability in a Terfenol-D vibration absorber.

## INTRODUCTION

PASSIVE vibration absorbers can be effectively employed to reduce undesirable vibrations in dynamical systems. A typical absorber architecture consists of a spring mass system which is attached to a target system and tuned such that its resonance frequency matches the frequency of the undesired vibrations [1,2]. Such design is thus useful for narrow band attenuation. The bandwidth overwhich the absorber is effective, however, can be increased substantially by incorporating tunability. Passive tuning methods include changing the effective mass or stiffness of the absorber system. Recently, active tuned vibration absorbers (TVA) based on adaptive or smart materials have been considered by means of which broadband tunability can be achieved in a simple manner by inducing changes in the active material through either electrical, magnetic, or thermal excitation. For example, shunted piezoelectric elements can be used to electrically change the stiffness of the TVA and thus its resonant frequency [3,4,5,6,7]. The modulus changes resulting from operation between the open- and short-circuit states, however, are small. In this paper, an extremely robust TVA which employs the giant magnetostrictive pseudobinary compound Terfenol-D ($Tb_{.3}\ Dy_{.7}\ Fe_{1.9–2.0}$) is demonstrated.

A passive tuned vibration absorber in its most basic configuration consists of a single degree of freedom spring-mass oscillator [1]. The absorber's fixed-free resonant frequency $f_o$ is tuned to match that of the undesired vibrations. When attached to a structure with excessive vibration characteristics, the added degree of freedom provides to the combined structure an additional resonant frequency near that of the absorber's, and one antiresonant frequency specifically at the absorber's resonant frequency $f_o$. Thus, the structure to which the absorber is attached will exhibit a reduction in the vibration level per input force at $f_o$, the frequency to which the absorber has been tuned. In real engineering systems, the damping due to the absorber materials will decrease the vibration attenuation at $f_o$. An increase in the absorber's mass increases the separation between the antiresonant frequency $f_o$ and the nearest two system resonant frequencies. Further details regarding passive absorbers can be found in References [1,2].

Recent work [3–7] on design and application of adaptive or tunable vibration absorbers examines the use of more complex absorbers that can be tuned to more than one resonant frequency thus providing vibration absorption at multiple frequencies. Following this concept, a tunable vibration absorber employing highly magnetostrictive Terfenol-D has been developed [8]. The tunable vibration absorber considered here consists of a Terfenol-D element, a wound wire solenoid, magnetic circuit components, an adjustable mechanical prestress mechanism, and an application-specific mass load. The magnetoelastic properties of Terfenol-D lead to changes in its elastic modulus with magnetic bias ($\Delta E$ effect) by over 160% [9] by means of varying the electric current into the solenoid. This basic operating principle can prove useful for applications requiring large forces, extended bandwidth, and "wireless" operation.

## BACKGROUND

The magnetically-induced strains exhibited by magneto-

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strictive materials arise as a consequence of the coupling between the interlattice spacing and the orientation of the magnetization. Changes in the orientation of the magnetization can be brought about by means of magnetic field, stress, or temperature changes. The reciprocity of the magnetostrictive phenomenon in fact implies two related effects, one which arises as the material strains under the action of a magnetic field and which facilitates actuation (Joule effect), and the other which arises as the magnetization changes under the action of stress (Villari effect) [10]. For the case of a magnetostrictive vibration absorber, an external DC magnetic field is used to provide a modulus change in the magnetostrictive material, with little regard to its output strain or force. It is noted that motion of the absorber and attached mass loads will apply a dynamic mechanical stress to the magnetostrictive material and thereby has the potential to influence the magnetization of the material through the Villari effect. This motion produces a back emf and a corresponding voltage in the solenoid that provides a measure of the absorber displacement.

In the early 1970s, the search for a material that exhibited large magnetostriction at room temperature grew out of the discovery of the extraordinary magnetic and magnetoelastic properties of rare earths. In particular, hexagonal terbium and dysprosium were found to have basal plane strains on the order of 1% at very low temperatures. Unfortunately, their magnetostriction reduced significantly near room temperature. Partial substitution of dysprosium for terbium in the Tb-Fe compound resulted in improvements in magnetic and mechanical properties. The most technologically advanced of these compounds is commercially available as Terfenol-D and has the composition $Tb_xDy_{1-x}Fe_y$, where $x = 0.3$ end $y = 2.0$ [11].

Terfenol-D provides a huge increase in strain capability, energy density, magnetomechanical damping, and sensitivity to stress over prior magnetostrictive materials such as nickel or iron [12-16]. In addition, Terfenol-D offers a very rich performance space given the sensitivity of performance to operating conditions [17]. This is particularly important for design of vibration absorbers, where the sensitivity of Young's modulus to the specific operating conditions and in particular to changes in magnetic bias is used for tuning the absorber to desired frequencies. As with all ferromagnetic materials, the application of an external magnetic field magnetizes the material by causing alignment of atomic magnetization vectors. A strain-applied field curve typical of Terfenol-D transducers field-induced magnetostriction is shown in Figure 1, where hysteresis has been neglected for simplicity. Three distinct magnetization regimes make up this curve [18]. In the low strain, low field regime (points 0–1), magnetic domain wall motion occurs. In the burst region, where tire strain-field slope is maximum (points 1–2), magnetic domain rotation between magnetically easy axes occurs. In the saturation regime, as the strain response approaches its saturation limit (points 2–3), magnetic domain rotation away from magnetically easy axes into alignment with the applied field direction occurs.

A schematic depicting the initial magnetization along with magnetization as a result of these three magnetization processes is given in Figures 2(a)–(d). The demagnetized state represented in Figure 2(a) shows that the material is composed of regions of permanently aligned magnetic moments, called domains, each one bearing a magnetization *Ms* (equal to what is called saturation magnetization) represented by the arrows. The magnetic domains are separated by thin transition regions called domain walls. In this configuration it is energetically favorable for the domain magnetizations to align randomly, thus causing the net magnetization in the

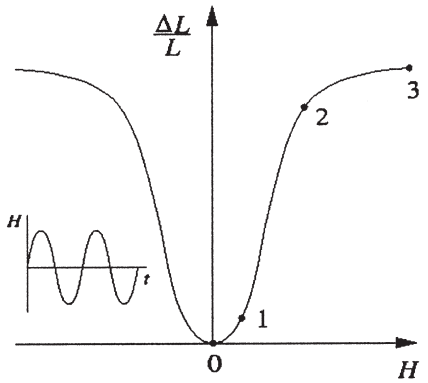


***Figure 1.*** *Anhysteretic strain-applied field relationship for magnetostrictive materials. Numbers 0–3 reflect strain at no field, low field, critical field, and saturation field respectively.*

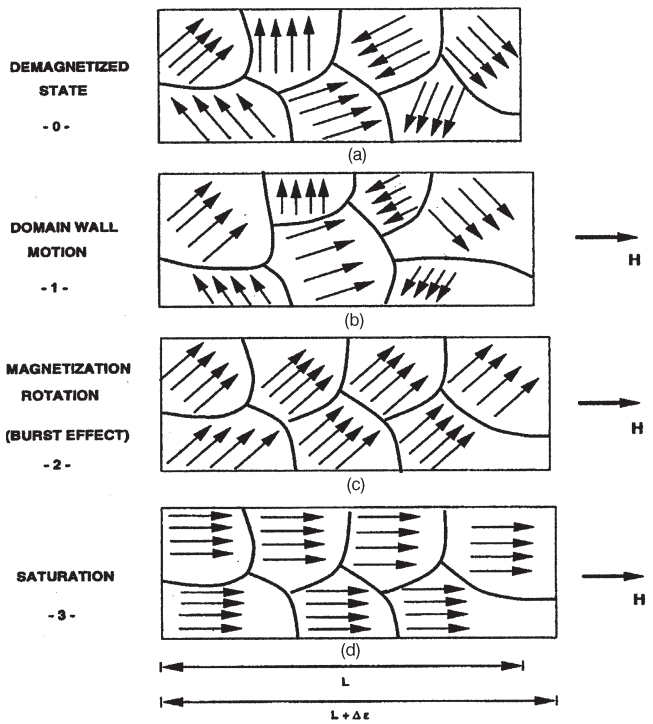


***Figure 2.*** *The magnetization processes. From top to bottom: (a) demagnetized state, (b) low strain region—domain wall motion, (c) burst region—rotation into easy axes closest to the applied field and (d) saturation magnetostriction region—domain rotation from easy axes into alignment with applied field.*

material to be zero. When a small magnetic field is applied, the original energy balance is broken and the domain walls translate and bow to accommodate the new energy balance in the material, as shown in Figure 2(b). Domains that were initially oriented favorably with respect to the applied field grow at the expense of domains opposing the applied field. As the field is further increased into the burst region, the domain magnetizations lying along easy crystallographic axes nearly perpendicular to the longitudinal axis of the rod "jump" to the easy axes nearly parallel to the field direction. This is depicted in Figure 2(c), where the magnetization vectors are parallel to one another but not quite oriented in the field direction. This configuration is achieved at values of the applied magnetic field known as critical field. In actuation devices, a magnetic bias nearly equal to the critical field is applied so as to center operation within the burst region. Finally, on application of a saturation field, the magnetization vectors are brought into complete alignment with the applied field direction as shown in Figure 2(d). The specific details on the domain processes taking place in each regime are also controlled by the crystal anisotropy, stress state, defects present in the material, and temperature as explained in detail in References [10,18–24].

## $\Delta E$ EFFECT

The definition of Young's modulus can prove problematic for materials with actively induced strain such as Terfenol-D. The strain and stress states interact with each other in a classical or mechanical fashion, but their relationship is also coupled to the magnetization state of the material. The Young's modulus is consequently a function of the magnetic state of the material and hence it cannot be considered to be a constant. The dual magnetostrictive process that relates the magnetic and mechanical states can be described with the two coupled linearized Equations (1a) and (1b). These equations of state for a magnetostrictive element are expressed in terms of mechanical parameters (strain $\varepsilon$, stress $\sigma$, Young's modulus at constant applied magnetic field $E_y^H$), magnetic parameters (applied magnetic field $H$, magnetic induction $B$, permeability at constant stress $\mu^\sigma$), and two magnetomechanical coefficients [the strain coefficients $d = (d^\varepsilon/dH) \,|\, \sigma$ and $d^* = (dB/d^\sigma) \,|\, H$].

$$\varepsilon = \sigma / E_Y^H + dH \tag{1a}$$

$$B = d^*\sigma + \mu^\sigma H \tag{1b}$$

Note that when subject to a constant or negligible applied field $H$, Equation (1a) yields the Hooke's relationship between stress and strain found in conventional nonmagnetostrictive materials. However, the uniquely large field-induced strain capability of Terfenol-D can produce strains of greater than 2000 microstrain, which are far larger than can be produced through the application of tensile or compressive stresses. Thus, the effective modulus of the material, as change in strain for a given change in stress, is very sensitive to applied field. Furthermore, the strain coefficient, $d$, is dependent upon $H$ to a first approximation. This situation gives the transducer/absorber designer extensive control of the system compliance by adjusting only one parameter, namely the applied magnetic field $H$.

For magnetostrictive materials, it is typical to reference two Young's moduli, one measured at constant applied magnetic field, $E_Y^H$, and one measured at constant magnetic induction, $E_Y^B$. In the first case, the modulus is measured while the magnetic field in the space of the material is held constant. This is usually accomplished by applying a DC magnetic field, generated with either a solenoid or a permanent magnet, while loading the rod with constant stress to avoid stress-induced magnetization effects. In the second case, the magnetic flux density inside the rod is held constant during testing, usually by means of feedback control of measured flux density. These two Young's moduli bracket the true operational value [14]. Although it is extremely difficult to maintain either of these two conditions during dynamic operation, the former case is close to the conditions under which the tuned absorber will operate.

Values of Young's modulus ranging from 20–60 MPa for $E_Y^H$ have been reported by Butler [16] and Flatau et al. [17], using quasi-static and dynamic techniques respectively. The Young's modulus can also be calculated from speed of sound measurements upon knowledge of the density of the material (nominal density of Terfenol-D is 9250 kg/m$^3$ [16]). The large variation in the reported values of the Young's modulus can be explained in terms of the effective operating conditions applied to the magnetostrictive core, namely stress, magnetization, and temperature. These operating conditions are dependent upon the specific transducer design, but for the tuned absorber presented here the mechanical preload and temperature are fixed, leaving the magnetic bias as the only control parameter.

The change in Young's modulus with applied DC magnetic bias, or $\Delta E$ effect, can be defined by

$$\Delta E = (E_H - E_0) / E_0 \tag{2}$$

where $E_H$ is the elastic modulus at magnetic field $H$, and $E_0$, is the elastic modulus at zero magnetic field. The $\Delta E$ effect is attributable to the magnetoelastic interactions in the material, which allow changes in magnetostriction beyond what would exist for purely mechanical operation. Since the modulus continues to change even above technical saturation, the field dependence of the elastic modulus cannot be explained with traditional domain motion considerations. According to Clark [18], the "unprecedented changes in modulus" arise from magnetoelastic interactions that produce an intrinsic softening of the crystal lattice due to local magnetoelastic atomic interactions as the field is reduced from the saturated value. Bozorth and others [10,22,23] discuss the $\Delta E$ effect in great detail.

Results from two 1975 publications are drawn upon to emphasize some of the prior experimental results related to the $\Delta E$ effect in Terfenol-D and to help motivate the current study on the application of Terfenol-D in a tunable vibration absorber. Clark and Savage [9] report changes in elastic modulus of 161% in samples subjected to saturation fields of 4.3 kOe. Data on the $\Delta E$ effect in $Tb_{.3}Dy_{.7}Fe_2$ taken from Reference [9] are shown in Figure 3. The Young's modulus is proportional to resonant frequency squared; hence the $\Delta E$ effect mirrors the achievable changes in absorber resonant frequency. Subsequent work by Savage et al. [18] presents resonant frequencies at constant field and constant induction, obtained from measurements of electrical impedance and admittance functions, respectively, for a free-free long thin bar of Terfenol-D. The actual mechanical resonance of the system occurs at a frequency slightly higher than the resonance at constant field [14,17], falling between the constant field and constant induction resonant frequencies. Data illustrating the variation in both resonant frequency at constant field and at constant induction due to the $\Delta E$ effect taken from Reference [19] are shown in Figure 4.

Experimental data by Butler [16] demonstrates the $\Delta E$ effect from a somewhat different perspective, as shown in Figure 5. Trends in the modulus under varied DC magnetic fields are shown for four different prestress levels (7,14, 21, and 28 MPa), illustrating the coupled relationship between mechanical and magnetic operating conditions. An initial decrease in the elastic modulus with applied magnetic bias is observed, possibly due to strain-induced softening. A minimum is reached near the so-called critical field value, where the change in strain is maximum for a given input magnetic field. Beyond this point, the magnetoelastic interactions dominate the material's behavior as explained by Clark [18], resulting in the material stiffening.

The results in Figure 4 show that magnetostrictive transducers are characterized by two resonant frequencies, one at constant magnetic field (magnetically free condition) and one at constant magnetic induction (magnetically blocked condition). This will be discussed briefly to clarify the distinction between the two elastic moduli associated with these two resonance states for a given operating condition and the variations in moduli associated with the $\Delta E$ effect due to changes in operating conditions. This situation can be explained by analyzing the linear constitutive Equations (1a) and (1b). Eliminating $H$ from Equation (1a) and $\sigma$ from Equation (1b) yields

$$\varepsilon = [(1 - dd^{*}E_Y^H / \mu^{\sigma}) / E_Y^H]\sigma + (d / \mu^{\sigma})B \qquad (3a)$$

$$B = (d^{*}E_Y^H)\varepsilon + [\mu^{\sigma}(1 - dd^{*}E_Y^H / \mu^{\sigma})]H \qquad (3b)$$

For a transducer, the "stiffest" operating case is modeled by assuming boundary conditions in which both the strain $\varepsilon$ and the induction $B$ are not allowed to vary; this corresponds to imposing blocked boundary conditions on the magnetostrictive sample. In Equations (3a) and (3b), the coefficients of $\sigma$ and $H$ (terms in square brackets) represent quantities associated with these stiff boundary conditions,

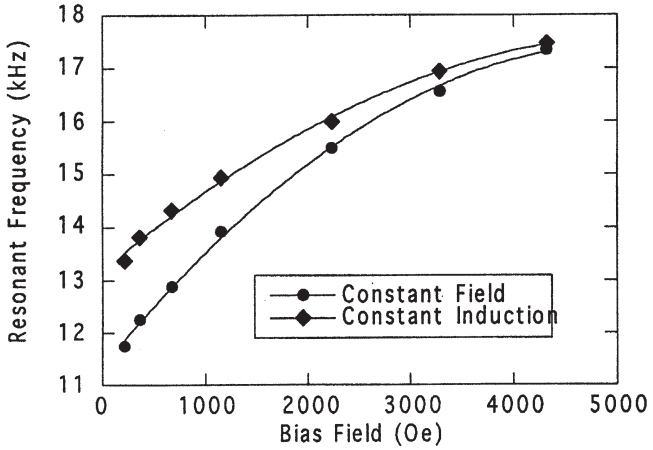


***Figure 4.*** *The influence of the $\Delta E$ effect on system resonant frequencies (from Reference [9], reprinted with permission © IEEE, 1975).*

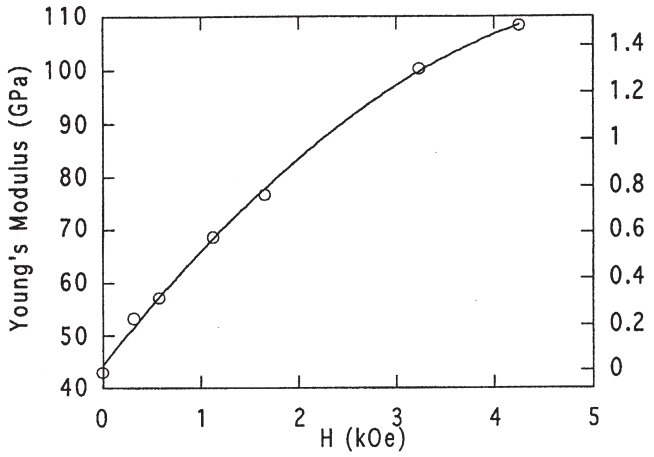


***Figure 3.*** *Young's modulus and the "ΔE effect" normalized to the no-field modulus for Terfenol-D versus DC magnetic field (from Reference [9], reprinted with permission © IEEE, 1975).*

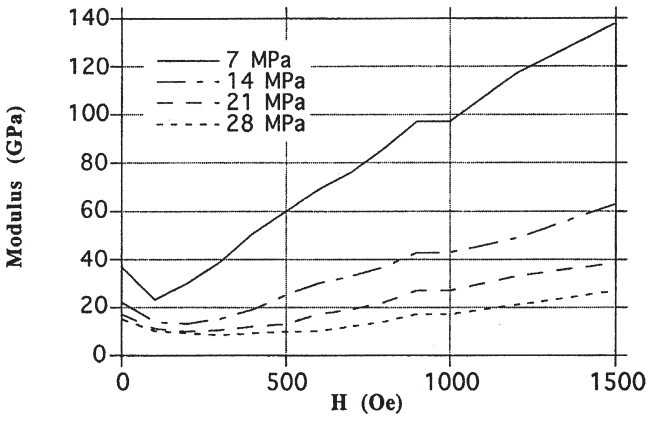


***Figure 5.*** *Young's modulus versus magnetic bias under four differentj prestresses: 7, 14, 21, and 28 MPa. Based on data from Reference [16].*

namely Young's modulus at constant induction, $E_Y^B$ and permeability at constant strain $\mu^\varepsilon$,

$$E_Y^B = (1 - dd^* E_Y^H / \mu^\sigma) E_Y^H \tag{4}$$

$$\mu^\varepsilon = (1 - dd^* E_Y^H / \mu^\sigma) \mu^\sigma \tag{5}$$

For a given applied field $H$ and applied stress $\sigma$, $E_Y^B$ and $E_Y^H$ bound the "stiffest" and "softest" elastic states of the magnetostrictive material as energy is converted back and forth between the elastic and magnetic states. Equations (4) and (5) lead to the definition of the magnetomechanical coupling factor $k$. As shown by Clark [17], the magnetomechanical coupling quantifies the maximum fraction of magnetic or elastic energies that can be transformed in the transduction process, and thereby provides a figure of merit for the transducer. The coupling factor is defined as

$$k^2 = dd^* E_Y^H / \mu^\sigma \tag{6}$$

From Equation (4) note that in the presence of increased energy conversion, the difference in the two Young's moduli ($E_Y^B$ and $E_Y^H$) increases. Hence, referring to Figure 4, for the given operating conditions, lower DC biases correspond to increased energy transduction and a wider range of elastic moduli. Citing Clark [17], this occurs because an increased portion of the system's total energy can be converted back and forth between magnetic and elastic energy.

The AC magnitude of the applied field $H$ also influences the difference between $E_Y^B$ and $E_Y^H$. Results in [16,25] show that with increasing excitation level the efficiency of the transduction process increases and both $E_Y^B$ and $E_Y^H$ decrease, with $E_Y^H$ decreasing more than $E_Y^B$. Thus, for a given DC bias or $\Delta E$ effect, variations in the AC field magnitude will modify the material moduli.

The tunable vibration absorber discussed in the next section uses the variation in Young's moduli produced by the $\Delta E$ effect, not the variation between moduli $E_Y^B$ and $E_Y^H$. (Note that a number of references on piezoelectric materials use variable shunt resistances to operate between these moduli [26].) In Figure 4, the $\Delta E$ effect is observed as variations in both $E_Y^B$ and $E_Y^H$ with applied DC field.

Summarizing this section, two elastic moduli are associated with a given set of operating conditions. These moduli provide a measure of the energy that can be transduced between the elastic and magnetic states of the material and bound the softest and stiffest elastic state of the material for a given AC and DC magnetic field. Larger variations in moduli are produced through the $\Delta E$ effect, with minimum and maximum moduli bounding the stiffest and softest elastic states of the material over a range of magnetic felds.

## TUNABILITY OF MECHANICAL RESONANCE

The capability to actively control a transducer's mechanical resonant frequency is a powerful design tool. The $\Delta E$ effect translates into a particularly easy to implement method for transducer mechanical resonance control. Again, these changes are initiated by varying the electrical signal in the transducer solenoid to produce a varying magnetic field. In addition, other transducer components such as prestress and mass load provide a means for tuning the nominal open circuit transducer mechanical resonance to a desired bandwidth. The result is a very rich frequency design space which provides unprecedented flexibility to the transducer designer and a simple electrical approach for adjusting the Terfenol-D absorber mechanical resonance.

The first axial mode mechanical resonance $f_o$ of a Terfenol-D transducer (in Hz) is given by

$$f_o = \frac{1}{2\pi} \sqrt{\frac{k_{T-D} + k_{mps}}{M_{eff}}} \tag{7}$$

where $M_{eff}$ is the effective dynamic mass, $k_{T-D}$ is the Terfenol-D core stiffness, and $k_{mps}$ is the prestress mechanism stiffness. The effective mass $M_{eff}$ is a combination of a portion of the mass of the rod, components in the prestress mechanism, the output connector, and any load to the transducer. For a long, thin Terfenol-D rod, the stiffness can be approximated by

$$k_{T-D} = \frac{E_Y A_{T-D}}{L_{T-D}} \tag{8}$$

with area $A_{T-D}$ and length $L_{T-D}$. From these equations, it is clear that increasing $E_Y$ increases $f_o$. The Young's modulus is dependent on the operating conditions, in particular magnetic bias, prestress, and magnetic drive level. The effect of the magnetic bias on the Young's modulus ($\Delta E$ effect) is quite complicated, as indicated by Figure 5. For a given prestress, the Young's modulus decreases to a minimum (nominally near the critical field) and then increases again with increasing field.

The transducer components, geometry, and other operating conditions will also affect the resonance. Since the prestress mechanism is generally in parallel with the Terfenol-D core, the effective stiffness of the system is the sum of the Terfenol-D core and the prestress mechanism. Therefore it increases with increasing stiffness of the prestress mechanism [Equation (7)]. The damping in the prestress mechanism will also affect the resonance; however this change will be slight relative to the effect of $k_{mps}$ and $M_{eff}$. The Terfenol-D geometry will also affect the resonance. From Equations (7) and (8), $k_{T-D}$ and hence $f_o$ increase with increasing $A_{T-D}$ and decreasing $L_{T-D}$. Note this simple analysis assumes no change in dynamic mass of the system, temperature, or prestress while the absorber is in use; i.e. the Young's modulus will vary in the fashion depicted by a simple modulus-DC field relationship for the appropriate system prestress, as depicted in Figure 5.

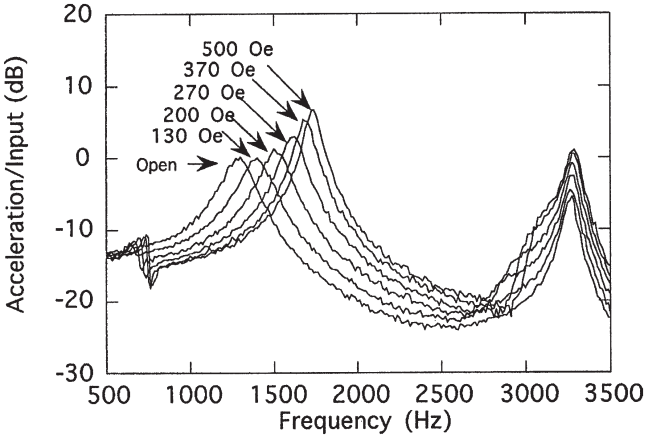


***Figure 6.*** *Absorber acceleration per current input to the shaker FRFs demonstrating the ΔE effect for shifting of the absorber mechanical resonant frequency.*

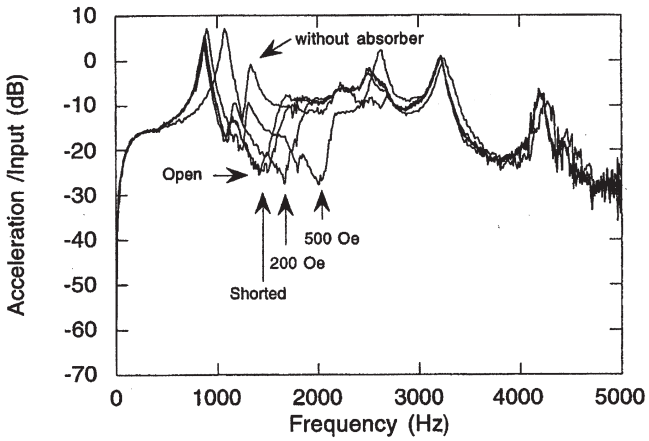


***Figure 8.*** *Acceleration per current input to the shaker frequency response functions demonstrating the ΔE effect for varying structural antiresonant frequencies.*

## EXPERIMENTAL RESULTS

Proof of concept experiments for demonstration of a tunable magnetostrictive vibration absorber were undertaken using a standard lab transducer and a structure designed to resonate at frequencies overlapping the transducer's open circuit fundamental resonant mode. The tunable vibration absorber considered here consists of a 0.63-cm-diameter, 5.08-cm-long Terfenol-D core, a 7.0 ohm (DC resistance) wound wire solenoid, magnetic circuit components including a permanent magnet with a strength of 250 Oe, an adjustable mechanical prestress mechanism, and an effective dynamic mass of 337 grams. A simple two-legged portal frame (one horizontal and two vertical metal bars bolted together) was designed and built, and its resonant frequencies were measured using broadband excitation from an Unholtz-Dickie 2000 $lb_f$ mechanical shaker. Acceleration responses were measured using PCB model UA353 accelerometers.

The absorber prestress was adjusted in small increments in the neighborhood of 7.0 MPa until the absorber open circuit resonant frequency matched that of the portal frame second mode at 1375 Hz. The influence of the $\Delta E$ effect was characterized by placing the absorber on the shaker and exciting it with 0–5 kHz broadband random noise. The absorber mechanical resonant frequency was measured for the following magnetic (electrical) loads: open circuit and DC fields of 130, 200, 270, 370, and 500 Oe. (Note that these fields were in addition to the 250 Oe provided by the permanent magnet.) Scaled frequency response functions (FRFs) of the absorber acceleration per current input to the shaker are shown in Figure 6. A measure of the bandwidth overwhich the absorber can be tuned is evident in that the absorber mechanical resonance varies from 1400 Hz to over 2000 Hz using under 2.0 amps of DC current into the 7.0-ohm solenoid used to provide the applied magnetic field. The transducer used had an upper current limit of approximately 2.0 amperes (600 Oe) due to the solenoid design; hence the influence of the $\Delta E$ effect at higher magnetic fields could not be observed.

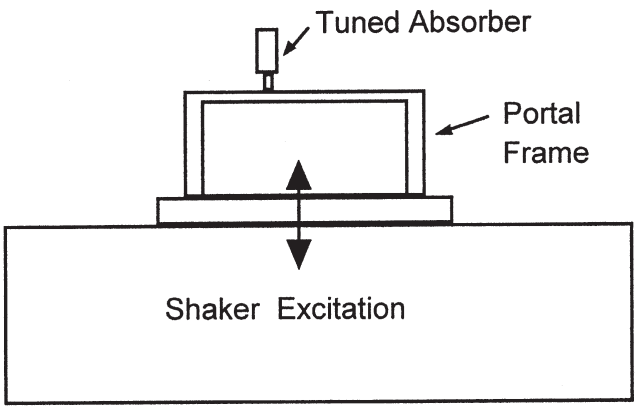


***Figure 7.*** *Schematic of the vibration absorption test configuration.*

The absorber was attached to the horizontal member of the portal frame as shown in Figure 7. The structure was excited using 0–5 kHz broadband random noise. The vertical acceleration of the portal frame horizontal member was measured. Scaled FRFs of the structural acceleration per current input to the shaker are shown in Figure 8. The frequency of the system's antiresonance was varied from 1375 Hz to 2010 Hz by using the $\Delta E$ effect. The upper frequency limit in these tests was constrained by this transducer's solenoid design, and was not due to having reached the upper limit of the $\Delta E$ effect modulus change. Replacing the Terfenol-D core with a piece of steel produced results quite similar to the open circuit results shown in Figure 8.

## CONCLUSIONS

Issues related to the design of a magnetostrictive Terfenol-D vibration absorber were discussed. Background on magnetostriction and the $\Delta E$ effect was presented in the context of the physical mechanisms that facilitate the high bandwidth tunability of the Terfenol-D vibration absorber. Prior work demonstrating the $\Delta E$ effect was reviewed to mo-

tivate the design of the Terfenol-D vibration absorber. Two relatively simple experiments were conducted to demonstrate proof of concept. These experimental results show use of the tunability of the Terfenol-D absorber for vibration control at frequencies from 1375 to 2010 Hz. It is emphasized that the huge modulus changes that give rise to this broadband tunability are due to the significant field-induced stiffening of the crystal lattice originated in the coupling between interlattice spacing and magnetization direction. These changes are approximately one order of magnitude greater than can be achieved with methods based on electrical shunting.

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