TERFENOL-D SENSOR DESIGN AND OPTIMIZATION

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ABSTRACT

The relatively large strain and force output of magnetostrictive Terfenol-D has led many researchers to focus on its uses for actuation. However, a Terfenol-D transducer can also be an effective sensor given the reciprocal nature of the magnetomechanical effects exhibited. In this paper a review of previous magnetostrictive sensor designs and technology and the associated theory is presented. A model for the force measured with a Terfenol-D transducer used to sense both force and acceleration is developed based on coupled linear magnetomechanical constitutive equations. The model which assumes real, constant coefficients fails to account for AC loses and therefore fails to account for phase shift with increasing frequency. The sensitivity of the sensor to force input is shown to be the highest for low prestress. Experimental verification shows the model is robust with respect to input force levels. The magnitude of the force calculated based on the model matches the force measured with a standard PCB load cell from 200 to 3000 Hz, the region in which constants are a good approximation of the model coefficients.

TERFENOL-D BACKGROUND

Magnetostriction is the change in the shape of a material due to a change in its magnetization. On a fundamental level, the change in dimensions results from the interactive coupling between an applied magnetic field and the magnetic moments of the material's individual domains. Giant magnetostrictive Terfenol-D ($Tb_X\ Dy_{1-X}\ Fe_Y$), an alloy of rare earths Dysprosium and Terbium with 3d transition metal Iron, is capable of bulk saturation strains in excess of $2000x10^{-6}$ at moderate magnetization levels at room temperature. Terfenol-D is currently produced in a variety of forms, solid (monolithic), powder (GMPC, giant magnetostrictive powder composite), and thin films. Its use as an actuator in applications requiring large displacements at both high and low frequencies is well documented, with applications including broadband shakers, surgical instruments, ultrasonic transducers, and many others.

Early work with magnetostrictives such as nickel, iron, and permalloy identified many uses for magnetostrictives as sensors as well. Some of the earliest uses of magnetostrictive materials from the first half of this century include telephone receiver [1], hydrophones, and scanning sonar [2], which were developed with Nickel and other magnetostrictive materials that exhibit bulk saturation strains of up to $100x10^{-6}$. In fact, the first telephonic receiver, tested by Philipp Reis in 1861, was based on magnetostriction [1]. Currently work continues to develop Terfenol-D applications as an actuator and as a sensor, including many scholarly papers and commercial patents. Examples of successful sensor designs include hearing aids, load cells, accelerometers, proximity sensors, torque sensors, magnetometers and many more [3,4,5,8].

SENSING EFFECTS

Various aspects of the coupling between the magnetization of the material and its magnetostriction can be employed to sense parameters of interest. Several effects which have application for sensing are discussed briefly. The Joule effect, the first thorough documentation of the magnetomechanical effect in 1842, is a longitudinal change in length due to an applied magnetic field. A transverse change in length and the associated volumetric change is also observed. Although this effect is usually associated with the actuation capability, numerous sensor configurations rely on the excitation of the magnetostrictor to facilitate sensing. The Joule effect has an important reciprocal effect known as the Villari effect; a stress induced in the material causes a change in the magnetization. This change in magnetization can be sensed, and once calibrated, used to measure the applied stress or force. The Villari effect has been the subject of much research [6,7,8] and has been employed in load cells, force cells, and accelerometers [4,8]. Another effect of interest is the Wiedemann effect, a twisting which results from a helical magnetic field, often generated by passing a current through the magnetostrictive sample. Twisting a magnetostrictive element or magnetized wire causes a change the magnetization which can be measured and related to the external torque. Over fifty patents have been issued in the last ten years based on the inverse Wiedemann effect, also known as the Matteuci effect, for magnetoelastic torque sensors [8].

Sensors based on Terfenol-D properties can be divided into three groups based on how the magnetomechanical properties of the Terfenol-D are used to measure the parameters of interest: 1. passive sensors, 2. active sensors, and 3. combined sensors. Passive sensors rely on the material's ability to change due to environmental stimulus to make measurements of interest. Passive sensors use the magnetomechanical effect such as the Villari effect to measure external load, force, pressure, vibration, and flow rates. Active sensors use an internal excitation of the Terfenol-D to facilitate some measurement of the Terfenol-D which changes with the external property of interest. For example, temperature can be determined by measuring the change in permeability, which is a function of temperature, of a Terfenol-D sample excited in a known manner. Designs which employ two coils, one to excite the Terfenol-D and one for measurement, are known as transformer type sensors. The most common active sensor design mentioned in literature is the non contact torque sensor. This employs variations on a general theme of using a magnetostrictive wire, thin film, or ribbon wrapped around or near the specimen which is subject to a torque. The change in the magnetic induction B can then be related to the torque on the specimen. Finally, combined sensors use Terfenol-D as an active element to excite or change another material which will allow measurement of the property of interest. For example a fiber optic magnetic field sensor uses the change in length of a magnetostrictive element in the presence of a magnetic field to change the optical path length of a fiber optic sensor [12]. There are numerous examples of combined sensors, including those to measure current, shock (percussion) and stress, frost, proximity and touch. Stress can be measured using photo elastic material, and highly accurate displacement measurements made with the help of a magnetostrictive guide. Fiber optics and diode lasers have been used with magnetostrictive elements to measure magnetic flux density (magnetometers) [8,3]. NDE applications have also been developed, such as a corrosion sensor for insulated pipes [13].

The existence of converse effects for each of the direct effects discussed above makes it possible for a magnetostrictive transducer to have two modes of operation, transferring magnetic energy to mechanical energy (actuation) and transferring mechanical energy to magnetic energy (sensing). As with many other transducer technologies such as electromagnetic (moving coils) and piezoelectricity, magnetostrictive transduction is reciprocal and a transducer has the ability to both actuate and sense simultaneously. Applications such as the telephone, scanning sonar, and others make use of this dual mode. For example a Terfenol-D sonar transducer can be used as either a transmitter or receiver or both at the same time. Another potential use of dual mode operation is in active vibration and acoustic control. One transducer can be used to sense deleterious structural vibrations and provide the actuation force to suppress them. Self-sensing control uses the sensed signal in a feedback loop to drive the transducer. Numerous papers have described this effect and shown its effectiveness [14].

THEORY

A model of the Terfenol-D transducer must incorporate both actuation and sensing capability. This can be accomplished by considering the coupling between the mechanical and magnetic energy of a magnetostrictive material. Equations 1 and 2 are the low-signal, linear, magnetostrictive constitutive equations commonly used to describe magnetostrictive behavior [16].

$$\varepsilon = \sigma / E_y^H + q\, H \tag{1}$$

$$B = q'\, \sigma + \mu^\sigma\, H \tag{2}$$

with strain ε, stress σ, Young's Modulus at constant applied magnetic field strength E_y^H, the magnetostrictive strain derivative (linear coupling coefficient) q ($d\varepsilon/dH|_\sigma$), magnetomechanical effect q´ ($dB/d\sigma|_H$), magnetic permeability at a constant stress μ^σ, applied magnetic field strength H, and magnetic flux density B within the Terfenol-D. The source of this equation is the linearization of the differential response of the ε and B to changes in only two factors, the applied field H and stress σ. It is not necessary to assume the coefficients (E_y^H, μ^σ, q, and q´) are single valued or linear, however this is generally the approach taken. Temperature, which is not considered here, is the third factor usually designated as primarily affecting magnetic and therefore magnetostrictive change [8]. Although the above variables are tensor quantities, only the axial direction will be considered, hence the subscripts indicating direction have been dropped. Several important assumptions are built into this magnetostrictive model. First, linear operation of the transducer is assumed. Although the magnetostrictive effect is nonlinear, for low signal levels, less than approximately one-third the maximum strain capability, the linear equations of magnetostriction provide a good first approximation. Second, the magnetostriction process is assumed to be reversible according to

$$q' = \left.\frac{dB}{d\sigma}\right|_H = \left.\frac{d\varepsilon}{dH}\right|_\sigma = q \tag{3}$$

where H is held constant for the first derivative and σ is held constant for the second. These two assumptions lead to a simplification of equations 1 and 2, since q = q´. Hysteresis evidenced in strain versus applied field plots proves this to be a poor assumption, however it provides a starting point for material modeling. This point will be considered in more detail later in this section. Finally, strain, stress, H, and B are assumed to be uniform throughout the Terfenol-D sample.

Clearly the interplay between the mechanical and magnetic effects is important. Magnetic domain wall motion and domain rotation and hence mechanical strain are produced by both mechanical stress and by applied magnetic fields. Similarly, the magnetic induction B will respond to the applied field H, as well as the mechanical stress. A first look at these equations tells much about the response of the material and the performance of a magnetostrictive transducer to external conditions. Increasing H will increase the strain output for a fixed prestress; similarly increasing the stress, which is compressive or negative in the equation, will decrease the strain for a fixed applied field. Magnetic induction B will increase with applied field H (or increased permeability) when the stress is kept constant and with decreasing (less compressive) stress when the applied field is kept constant.

A simple model of the sensing capability of the transducer can now be developed. Solving equation 1 for H and substituting into equation 2 yields

$$B = \sigma\ (q - \mu^{\sigma} / q\ E_y^H) + \varepsilon \mu^{\sigma} / q$$

According to Faraday's law, the voltage induced in a coil of N turns and cross sectional area A surrounding the Terfenol-D sample is

$$V = NA\ dB/dt = NA\ d\sigma/dt\ (q - \mu^{\sigma} / q\ E_y^H) + NA\ d\varepsilon/dt\ \mu^{\sigma}/q \qquad (4)$$

assuming system parameters μ^{σ}, q, and E_y^H do not vary with time. Of the three terms which make up the right hand side of equation 4, the first two are proportional to the time derivative of force (proportional to jerk) while the last is proportional to the time derivative of strain (or proportional to velocity). The first term would be the only one needed if the system could be decoupled and changes in magnetization were a result solely of impressed force. However since a model of the magnetomechanical effect requires the use of coupled equations that also incorporate the impact of an impressed force on the H field, the second term, which is 180 degrees out of phase with the first, and the final term, which is in phase with the first, must be included.

For harmonic excitation equation 4 becomes

$$V = NA(2\pi f)\sigma\ (q - \mu^{\sigma} / q\ E_y^H) + NA\varepsilon(2\pi f)\mu^{\sigma}/q \qquad (5)$$

The right side of equation 5 can then be evaluated to determine the relative size of the three terms. Typical values for the parameters in equation 5, taken from experimental work and literature, are given in table 1. The first and second terms are the same order of magnitude, while the third term is an order of magnitude smaller. (The third term would be equal in magnitude but opposite in sign to the second term if strain was simply stress divided by Young's Modulus, however equation 1 indicates this will not be the case.) Accordingly only the first and second terms of equation 5 will be used to compute the force ($F=\sigma A$) based on the voltage induced in the coil surrounding the Terfenol-D core. The force measured by the Terfenol-D sensor can be found from equation 6.

$$F = \frac{V}{N(2\pi f)} \left[\frac{1}{q - \mu^{\sigma} / (q E_y^H)} \right] \qquad (6)$$

Harmonic excitation was assumed earlier in the development, however equation 6 holds for any arbitrary signal if $V/2\pi f$ is set equal to the integral of V with respect to time. This model will be compared with experimental data in the next section.

In order to make the most sensitive Terfenol-D sensor, it is important to optimize its design and performance criteria. The transducer can be optimized with respect to prestress, magnetic bias, load and frequency of operation. Equation 6 shows the sensitivity V/F is directly proportional to the number of turns N. In addition the sensitivity increases as the ability of the material to magnetize increases (μ^{σ} increases), and decreases as the material becomes less mechanically compliant (E_y^H increases).

Material Property	Young's Modulus E_y^H (GPa)	Permeability μ^σ (Tm/A)	strain coefficient q (m/A)	coupling factor k^2
Butler [9]	25-30	11.56e-6	15e-9	0.7-0.75
ISU study [15]	50-60	2.2-6.7 e-6	3-4.5 e-9	0.35-0.5
Value used	60	2.2e-6	4.5 e-9	0.4

Table 1: Experimental and published values for magnetostrictive Terfenol-D transducer material properties.

The ideal Terfenol-D sensor for measuring compressive forces would have the lowest magnetic bias that is sufficient to just align all the magnetic domains parallel with the axis of the applied stress. The magnetic bias or "critical field" which provides this alignment causes a step change in magnetization and strain due to rotation of the domains from one easy axis to another located at a 90 degree angle [10]. For sensing, the mechanical stress will rotate the domains causing a large change in magnetization which is measured as the sensing signal. Using a low critical field corresponds to a high sensor sensitivity, as the sensor has the least opposition to change by an external force. In general the critical field increases with increasing prestress [11], thus implying that use of the lowest allowable mechanical prestress will result in the most sensitive sensor.

Equating q and q´ as shown in equation 3 is based on thermodynamic equilibrium, assuming a reversible magnetization process with no losses. This implies that operating Terfenol-D under conditions that maximize the magnetostrictive strain derivative $d\varepsilon/dH|_\sigma$, for increased actuation, will simultaneously result in a large magnetomechanical effect $dB/d\sigma|_H$, causing an increased sensing capability to be realized. Thus the optimization of the actuation capability (q) should correspond to an optimization of the sensing sensitivity (q´) and increased efficiency for actuation translates into increased sensitivity for sensing. This conclusion is mentioned in the Naval report, "The design and construction of magnetostriction transducers" (dated 1946, pg. 370), referring to the design of a magnetostrictive scanning sonar transducer: "Higher efficiency of the transducer as a transmitter gives it greater sensitivity as a receiver." This implies that the transduction process is reciprocal in nature. In other words, energy can be transferred from the mechanical to magnetic state (sensing) most efficiently under the same conditions for most efficient energy transfer from the magnetic to the mechanical state (actuation).

Earlier work by the authors has shown peaks in performance, in particular q, with prestress and magnetic bias. When the transducer used in this study was operated as an actuator a peak in q was found under a bias condition of 6.9 MPa (1.0 ksi) and 33.2 kA/m (415 Oe) [11]. Therefore one might expect that when the transducer is operated as a sensor a similar peak in sensitivity will be found under the same bias conditions. This is in contrast with the physical argument regarding overcoming the critical field presented above. However, neglecting losses may be a poor assumption for normal transducer operation given the presence of eddy currents and hysteresis. Jiles discusses in detail the significance of the hysteretic irreversibility of magnetization and magnetostriction and concludes that it is necessary to consider the losses [6]. This suggests the importance of judicious use of equation 3, since it is appropriate only under certain conditions. Attempts to optimize the sensor sensitivity showed that equation 3 does not provide a basis for optimization with respect to prestress and magnetic bias.

RESULTS

In this paper results show the utility of a standard broadband transducer as a sensor. The experimental data reported here was taken from a broadband Terfenol-D transducer developed at Iowa State University [17,18]. It was originally designed as an actuating device but used in the configuration shown in figure 1 to measure force or stress. It was designed to produce an output free of spurious resonances, and to allow adjustable prestress and magnetic bias. A two inch long, quarter inch diameter laminated Terfenol-D rod ($Tb_{0.3}Dy_{0.7}Fe_{1.9}$) was placed inside two coils, an inner single layer 110 turn pick-up coil, and a multi-layer 1100 turn drive coil. In sensing mode either coil could be used to measure the magnetic flux density. A current control amplifier (Techron 7780) provided the input to the drive coil to produce a DC magnetic bias as needed. Additional magnetic bias was provided by a slit, cylindrical permanent magnet which surrounded the coils. Washers in series with the Terfenol-D rod provided a mechanical prestress, which could be varied with a prestress bolt which threaded into the base and pushed the rod into the washers. The measurable quantities from the transducer included the current and voltage in the drive coil, voltage (proportional to the time derivative of B) induced in the pick-up coil, and the mechanical input, force. Note again that the magnetostrictive sensor measures the time derivative of the load rather than the load itself, thus requiring integration hardware or software.

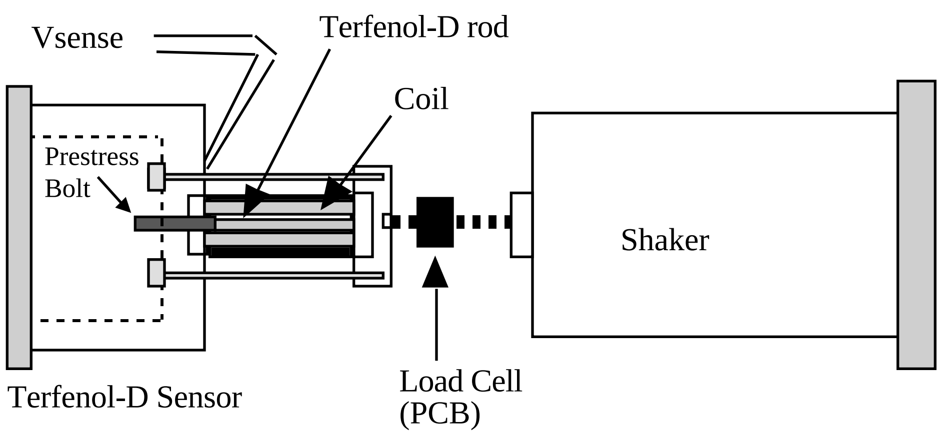

Figure 1: Testing setup for Terfenol-D transducer used as a force sensor.

The first set of tests were completed to optimize the sensitivity of the sensor with prestress. The optimization of the sensor sensitivity was evaluated in terms of voltage output per force input. The shaker was driven with a broadband 0-5000 Hz signal generating 10 N rms force across this bandwidth. Table 2 shows the 0-5 kHz rms voltage per Newton force for four different prestresses with 12 kA/m (150 Oe) magnetic bias: 1. 0.79 MPa (100 psi), 2. 1.60 MPa (200 psi), 3. 3.98 MPa (500 psi), and 4. 7.96 MPa (1000 psi). Although a full optimization study addressing interaction of prestress and magnetic bias was not performed, the sensitivity clearly decreases with increasing prestress from a peak of 109 mV/N at 0.79 MPa, 12 kA/m. A minimum prestress value of 0.79 MPa was needed to keep the Terfenol-D rod in place during testing.

Test Number	Prestress (MPa)	Sensitivity (Vsens/N)
1	0.79	0.109
2	1.6	0.104
3	3.98	0.089
4	7.96	0.075

Table 2: Sensitivity in Volts per Newton force at 12 kA/m magnetic bias and four prestress levels.

The measurement of the force or stress (dividing the force on the Terfenol-D rod by the area of the rod) was accomplished by connecting the transducer to another broadband transducer and blocking both ends, see schematic in Figure 1. Limitations of the test stand used in this proof of concept study constrained the blocked force performance to under 10 N from 0 to 10 kHz. A PCB model 208A03 load cell was placed in series with the shaker and the sensor transducer.

The load from the load cell, and voltage induced in the drive coil of the sensor were monitored for broadband (1 Hz to 5 kHz) random excitation. For these tests the sensor transducer was given a prestress of 0.79 MPa (100 psi) and magnetic bias of 12 kA/m (150 Oe). Figure 2 shows the force as a function of frequency from the load cell and from the sensor calculated from equation 6, where values for q, μ^{σ}, and E_y^H were taken from Table 1. The force calculated from equation 6 matches the measured force in magnitude from approximately 200 Hz to well over 3.0 kHz, a bandwidth over which the use of constants to characterize q, μ^{σ}, and E_y^H is a good approximation. At higher frequencies the effect of the sensor resonance becomes appreciable. At low frequency the lack of agreement is attributed to the fact that the coefficients, in particular q, are very sensitive to changes in frequency. Example time traces of the force from the PCB load cell and the sensor using equation 6 with a sinusoidal excitation of 500 Hz are shown in Figure 3. Excellent agreement between the two forces is seen in amplitude and phase, the only difference being the lag of the sensor signal on the ascending slope, which is a result of harmonic distortion. Figure 4 shows the transfer function magnitude and phase between the force measured by the sensor using equation 6 and the force measured by the load cell. The magnitude of the transfer function is close to one from 250 Hz to 3000 Hz, substantiating the agreement seen in Figure 2. According to Figure 3, at 500 Hz the phase between the two force signals is off by about 10 degrees, with the sensor lagging the load cell. This phase lag problem points to a limitation of the model. Assuming the coefficients q, μ^{σ}, and E_y^H are linear, constant, and real, limits the frequency range where this model is applicable. This model does appear to be fairly robust with respect to force levels since the same values for q, μ^{σ}, and E_y^H provided an excellent fit for 500 Hz sinusoidal excitations at both 1 and 10 N.

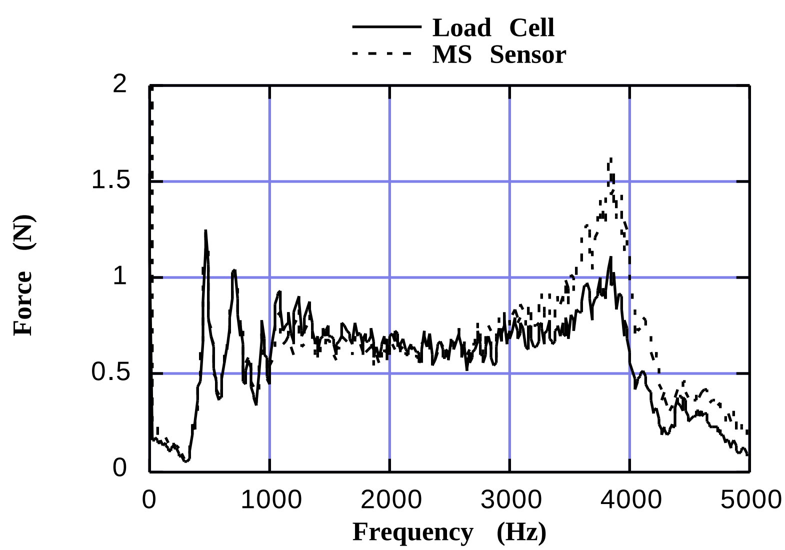

Figure 2: Comparison of the load cell force and force measured by the Terfenol-D sensor using equation 6 versus frequency.

The ability to sense vibrations was also tested in a blocked-free configuration in which the sensor acted like an accelerometer. In this case the shaker, load cell, and sensor were stacked vertically, i.e. Figure 1 rotated 90 degrees clockwise, so the shaker was blocked at the lower end and the sensor was free. The transfer function between force calculated from equation 6 and the force measured by the load cell versus frequency is shown in Figure 5. In this configuration both the load cell and the Terfenol-D are measuring acceleration, force divided by the mass of the sensor (approximately 0.75 kg). The magnitude remains relatively flat out to around 2000 Hz similar to the blocked-blocked case in Figure 4, however the phase is decreasing much more quickly as the frequency approaches the sensor resonance. Equation 6 was applied to this configuration with the same coefficients shown in Table 1. In this case the fit is rather poor, with the magnitude is off by approximately a factor of five. This does not invalidate the model but merely points out the sensitivity of material properties coefficients, q, μ^σ, and E_y^H to operating conditions and operating configuration.

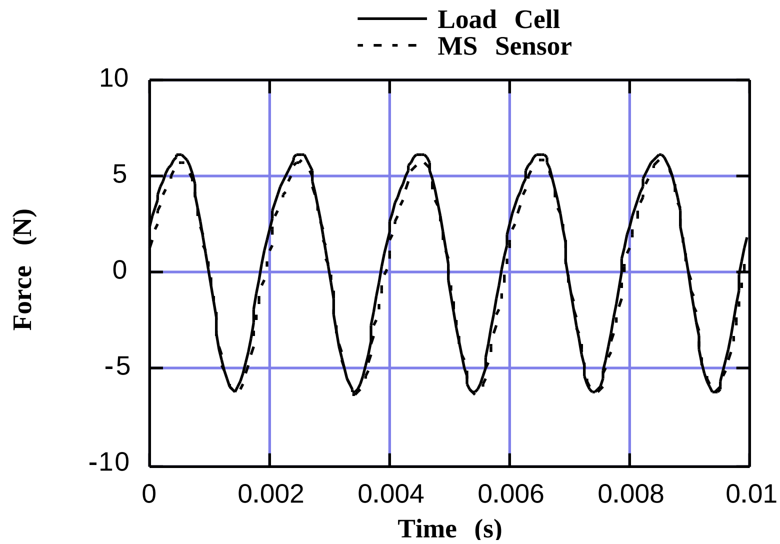

Figure 3: Comparison of time domain force measured by the load cell and measured by the Terfenol-D sensor using equation 6.

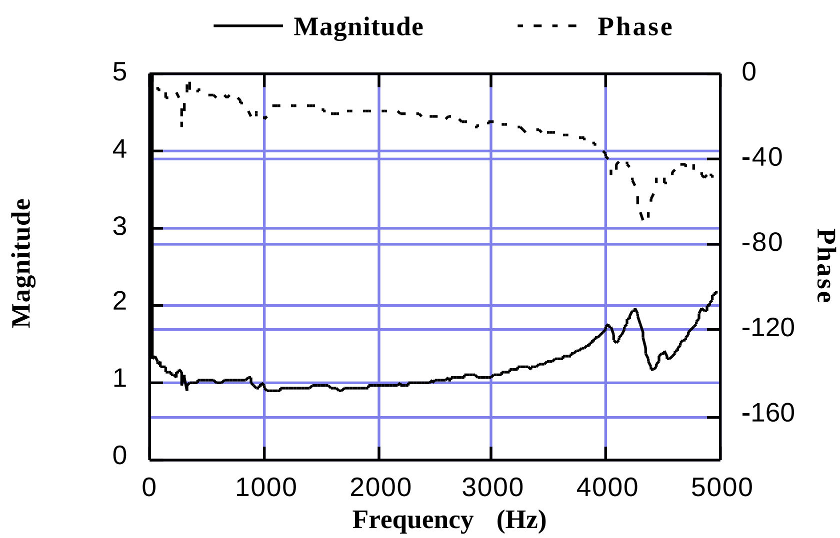

Figure 4: Transfer function between the force measured by the Terfenol-D sensor using equation 6 and the force measured by the load cell.

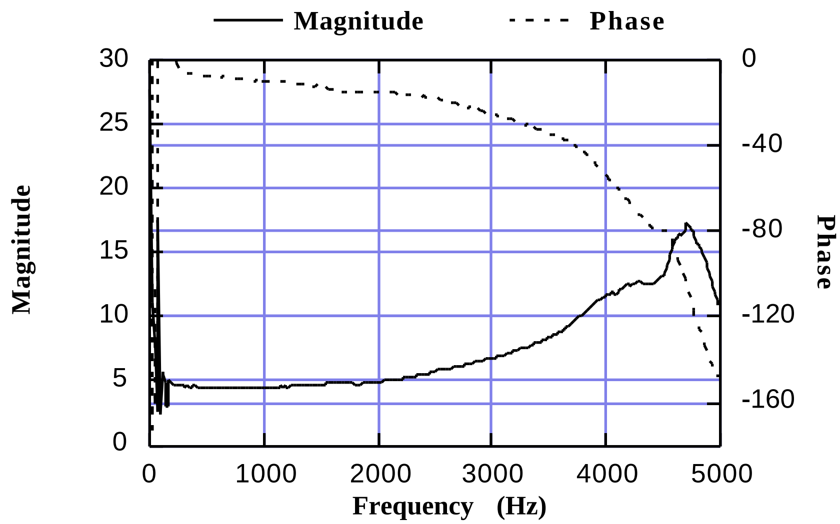

Figure 5: Transfer function between force measured by the Terfenol-D sensor using equation 6 and the force measured by the load cell in blocked free configuration.

CONCLUSION

A model for the force measured with a Terfenol-D transducer used to sense both force and acceleration is developed based on coupled linear magnetomechanical constitutive equations. Experimental verification shows the model allows the Terfenol-D transducer to accurately measure the force over a range of frequencies where a constant provides a good approximation of model coefficients, in particular q. The coefficients in the model, E_y^H, μ^σ, q, and q´, are taken from prior tests of the transducer used as an actuator. They are assumed to be real and constant, resulting in the failure of the model to account for AC loses and phase shift with frequency. The sensitivity of the sensor to force input is shown to be the highest for low prestress with a magnetic bias close to the critical field. A peak sensitivity of 109 mV per Newton force was obtained with a 12 kA/m magnetic bias and 0.79 MPa prestress.

ACKNOWLEDGMENTS

This work was supported by the Graduate Student Research Program, NASA Langley (Dr. Richard Silcox technical advisor), and a National Science Foundation Young Investigator Award.

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