DEVELPOMENT AND ANALYSIS OF A SELF-SENSING MAGNETOSTRICTIVE ACTUATOR DESIGN

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ABSTRACT

A self-sensing magnetostrictive actuator design based on a linear systems model of magnetostrictive transduction for Terfenol-D is developed and analyzed. Self-sensing, or the ability of a transducer to sense its own motion as it is being driven, has been demonstrated for electromechanical transducers such as moving voice coil loudspeakers and, most recently, piezoelectric distributed moment actuators. In these devices, self-sensing was achieved by constructing a bridge circuit to extract a signal proportional to transducer motion even as the transducer was being driven. This approach is analyzed for a magnetostrictive device. Working from coupled electromechanical magnetostrictive transduction equations found in the literature, the concept of the transducer's "blocked" electrical impedance and motional impedance are developed, and a bridge design suggested and tested. However,

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First presented at the SPIE/ASME/SEM North American Conference on Smart Structures 2/93.

results presented in this paper will show that magnetostrictive transduction is inherently non-linear, and does not, therefore, lend itself well to the traditional bridge circuit approach to self-sensing.

1.INTRODUCTION

Magnetostriction, or the tendency of certain materials to strain in the presence of a magnetic field, is a well known phenomenon that was "discovered" by Joule who published his findings on the effects of magnetism on iron and steel bars back in 1847 (Hunt, 1982). Recently, a manufacturing process has been developed for alloying iron with the rare earth metals terbium and dysprosium to produce a material capable of magnetically induced strains on the order of 2000 ppm, the "giant" magnetostrictive material, Terfenol-D. Transducers have been fabricated from Terfenol-D by placing a rod of the material in a wire solenoid and subjecting the coil to an alternating current. The resulting magnetic flux causes vibrations in the rod which can be mechanically coupled to other structures. The transducer, so designed, is a vibration source (Hall and Flatau, 1992), and much research is underway to investigate the utility of these actuators for active vibration control.

Terfenol-D actuators can produce force levels comparable to moving armature vibrators ten times their size and are capable of strains in excess of their piezoelectric counterparts; they are thus quite attractive for vibration control. So far, magnetostrictive transducers have been used successfully for vibration control in a beam, and as an active isolation mount for a mass subject to base excitation (Flatau et al., 1992, Hiller et al., 1989). The material can also be used as a sensor, since, as would be expected, there exists a converse magnetostrictive effect (Villari effect), though little research has been done in this area to date.

This paper considers the possibility of using a single magnetostrictive transducer as both sensor and actuator to achieve a self-sensing actuator as was described by Dosch et al. (1992) for a piezoelectric element. The motivation for a self-sensing actuator is that it is capable of truly collocated control. In addition, a self-sensing actuator is attractive from the standpoint of minimizing the amount of instrumentation required to control a structure. An actuator/sensor pair in a single package cuts instrumentation in half and reduces the number of system elements subject to failure for structural control applications such as large space structures where fault tolerance and system redundancy are issues.

The paper begins with a discussion of magnetostrictive transduction as it applies to a prototype vibration source or shaker which uses a Terfenol-D rod as a drive element. The fundamental equations as posed in Bulter (1988) are restated in a form which suggests a method of achieving a self-sensing actuator. An equivalent electrical circuit model is proposed. From this electric circuit model, a bridge circuit for measuring a voltage proportional to strain is developed and analyzed. The concept of an electromechanical transducer's driving point electrical impedance is reviewed as well as the concepts of blocked and motional impedances.

Finally, experimental results are presented which strongly suggest a reassessment of the conventional simplified linear models for magnetostrictive materials. Measurements of "blocked" driving point impedance are shown to vary not only as functions of frequency but as functions of current amplitude. An explanation of the results is hypothesized and recommendations for further research suggested.

2. MAGNETOSTRICTIVE TRANSDUCTION

A theoretical basis for a self-sensing Terfenol-D actuator can be derived from equations that model its electromechanical coupling, or transduction properties. We present the constitutive equations for Terfenol-D in their general form and then make simplifying assumptions to develop a set of equations that describe an idealized uniaxial transducer made from the material. We briefly review a general method for analysing electromechanical devices using coupled electrical and mechanical impedances and within this framework illustrate the concept of self-sensing. Finally, the constitutive equations for our idealized transducer are recast in terms of electrical and mechanical impedances to facilitate the development of a bridge circuit for self-sensing.

Equations relating applied magnetic field to induced strain for magnetostrictive materials may be found in the IEEE standards for magnetostrictive materials (1976,1983). Terfenol-D's manufacturer, ETREMA Products, Inc., also publishes a version of these equations in an application manual for designers (Butler 1988). From this application manual we obtained the following relations:

$$S_j = \sum s_{ji}^{H} T_i + \sum d_{ji} H_i \tag{1}$$

$$B_j = \sum d_{ji} T_i + \sum \mu_{ji}^{T} H_i \tag{2}$$

where S is the strain, s is the compliance, H is the magnetic field intensity, B is the flux density, T is the mechanical stress, d is the piezomagnetic strain constant, and μ is the permeability. The H superscript on the compliance implies that it should be evaluated for a constant applied magnetic field. Similarly, the T superscript on the permeability implies that it should be evaluated while the material is subject to a constant mechanical stress.

Equations (1) and (2) assume an arbitrary piece of magnetostrictive material subject to three dimensional stress and magnetic fields. We simplify the problem by considering a slender rod of Terfenol-D with one end fixed and the other end free to move longitudinally. An idealized solenoid wrapped around the rod is assumed to produce a magnetic field that is of uniform strength across the rod's cross section for the entire length of the rod and is directed longitudinally. As a first approximation, we also assume linear elastic and magnetic material properties. With these assumptions, the general three dimensional relations reduce to the following :

$$\varepsilon = \frac{\sigma}{E_y} + dH \tag{3}$$

$$B = d\sigma + \mu^{\sigma} H \tag{4}$$

where ε is the induced uniaxial strain, E_y is the modulus of elasticity for Terfenol-D in the absence of a magnetic field, and σ is the applied uniaxial stress.

Equation (3) shows that the strain in the material is due to two factors: the applied stress (Hooke's law) and the applied magnetic field intensity (direct magnetostriction or the Joule effect). Similarly, equation (4) relates flux density to applied mechanical stress (converse magnetostriction or the Villari effect) and to the applied magnetic field intensity (magnetization).

Electromechanical transducers are typically analysed using electric-circuit analogies, a thorough treatment of which appears in a monograph by Hunt (1982). The conversion of electrical energy to mechanical is modeled by using an electric circuit comprised of a voltage source and an equivalent electrical impedance coupled to a mechanical "circuit" comprised of a mechanical force acting on an equivalent mechanical impedance. The coupling of the two circuits occurs through a "black box" called a transducer as illustrated in figure 1.

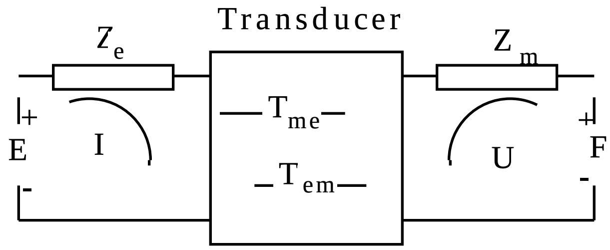

Fig. 1. Schematic representation of an electromechanical transducer (Hunt, 1982)

For any electromechanical device, it follows from figure 1 that the Laplace transformed transduction equations have the following form:

$$E = Z_e I + T_{em} U \tag{5}$$

$$F = T_{me} I + Z_m U \tag{6}$$

where E is the Laplace transform of the voltage applied across the input electrical terminals of the transducer, Z_e is the "blocked" electrical impedance (the complex impedance measured when the mechanical system is constrained from moving), I is the Laplace transformed current in the electrical circuit, T_{em} is a transduction coefficient that represents the electromotive force appearing in the electrical circuit per unit velocity in the mechanical circuit, U is the Laplace transformed velocity in the mechanical circuit (motion of the free end of the Terfenol rod in this case), Z_m is the mechanical impedance (measured when the electrical side is open circuited), and T_{me} is a transduction coefficient that represents the force acting in the mechanical circuit per unit current in the electrical circuit.

To explain the theory behind the self-sensing magnetostrictive actuator, it will be convenient to express equation (4) in terms of electrical and mechanical impedances as in equation (5). However, before doing this, we'll use equation (5) to explain how self-sensing has been achieved in other electromechanical devices.

Equation (5) shows that the voltage drop across the terminals of any electromechanical transducer is the sum of two terms; one is proportional to the current applied to the device and the other is proportional to the velocity this current induces in the electromechanical system. This implies that a signal proportional to the induced velocity can be obtained by measuring the voltage across the transducer terminals and subtracting from it a voltage equal to $Z_e I$. A bridge circuit as illustrated in figure 2 can perform the subtraction. Here, the velocity is proportional to the voltage E_1-E_2, which is simply the voltage across the bridge.

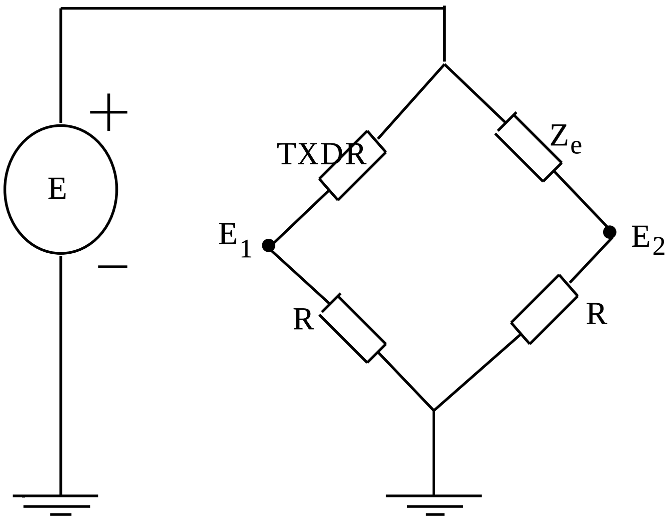

Fig. 2. Bridge circuit for sensing while actuating

The bridge circuit method for self-sensing was first proposed for "motional feedback" control of moving voice coil loudspeakers, where it was claimed that if the differential signal was fed back through the power amplifier it would damp the mechanical resonance of the speaker (De Boer, 1961). Recently, similar strategies have been adopted for piezoelectric transducers in structural vibration control. These efforts have used bridge circuits to obtain collocated strain, and rate of strain feedback control, as well as positive position feedback control (Dosch et al., 1992, Hagwood et al., 1991).

We seek to apply the bridge circuit method to our idealized magnetostricive transducer. Hence, we return to the problem of manipulating equation (4) into the form of equation (5).

If both sides of equation (4) are multiplied by the cross-sectional area of the rod, A, then the following expression is obtained:

$$\varphi = dA\sigma + \mu^{\sigma}HA \tag{7}$$

where φ is the magnetic flux through the rod. For a rod in a wound wire solenoid the applied field intensity, H, is the product of the current through the solenoid, i(t), and the number of turns in the coil, n:

$$H=i(t)n \tag{8}$$

Furthermore, the open circuit voltage, e(t), is:

$$e(t) = N\frac{d\varphi}{dt} \tag{9}$$

where N is the product of the number of turns, n, in the coil and the solenoid length, l. Taking the time derivative of equation (7) and multiplying the result by N, the relationship for the voltage across a magnetostrictive transducer is :

$$e(t) = NdA\frac{d\sigma}{dt} + \mu^{\sigma}N^{2}\frac{A}{l}\frac{di}{dt} \tag{10}$$

The stress is related to the strain by Young's modulus for frequencies well below the rod's first longitudinal resonant mode. Thus, equation (10) can be rewritten as:

$$e(t) = NdAE_{y}\frac{d\varepsilon}{dt} + \mu^{\sigma}N^{2}\frac{A}{l}\frac{di}{dt} \tag{11}$$

which can be rewritten in terms of velocity, u(t), as:

$$e(t) = Nd\frac{AE_{y}}{l}u(t) + L\frac{di}{dt} \tag{12}$$

where the product of the coefficients in front of di/dt in equation (11) is equal to the inductance, L, of a solenoid with a Terfenol-D core assuming that the magnitude of field variations to be considered is sufficiently small that the permeability of Terfenol-D is approximately a constant and independent of flux. Finally, we take the Laplace transform of equation (12), assume harmonic forcing and obtain an expression in terms of electrical and mechanical impedances:

$$E = Nd\frac{AE_y}{l}U + j\omega LI \qquad (13)$$

Comparing equation (5) to equation (13), we conclude that the transduction coefficient, T_{em} , is the product of the coefficients in front of the velocity, U, and that the blocked impedance, Z_e , is proportional to the inductance, L, of our idealized solenoid. One could also replace the area, Young's modulus, and length terms by a single variable representing the Terfenol rod equivalent spring constant:

$$k = \frac{E_y A}{l} \qquad (14)$$

Similar to the just completed derivation, equation (3) can be manipulated into the form of equation (6), and the coupled transduction equations for a Terfenol-D magnetostrictive transducer can be expressed as follows (Pratt, 1993):

$$E = E_y AdnU + j\omega LI \qquad (15)$$

$$F = k\frac{1}{j\omega}U - E_y AdnI \qquad (16)$$

Observe that $T_{me} = -T_{em}$. This is typical of magnetically coupled transducers, and presents some difficulties for the construction of equivalent electrical circuit models.

3. EQUIVALENT ELECTRICAL MODEL

In the previous section, the simplified transduction equations (3) and (4) were manipulated to reveal the underlying electrical and mechanical impedances of the two port system illustrated in figure 1. The resulting equations (15) and (16) will now be stated in the form of an equivalent electrical circuit using the well known concept of an ideal transformer (Hunt, 1982). Because of the antisymmetric nature of these coupling equations, some creativity is required in the construction of the equivalent circuit. A variety of methods exist to address this problem, including the use of a circuit element known as a gyrator whose behavior mimics the coupling of a gyroscope. A fairly straight forward approach, referred to as the mobility method (Hunt, 1982), is to restate the equations using a force-current analogy instead of force-voltage. This technique yields the following coupled equations:

$$E = \left(Z_e - \frac{T_{em} T_{me}}{Z_m} \right) I + \frac{T_{em}}{Z_m} F \tag{17}$$

$$U = \frac{T_{me}}{Z_m} I + \frac{1}{Z_m} F \tag{18}$$

An equivalent circuit for this system of equations is shown in Figure 3. This circuit can be redrawn using an ideal transformer that yields the circuit of Figure 4, where appropriate values of the coefficients have been substituted.

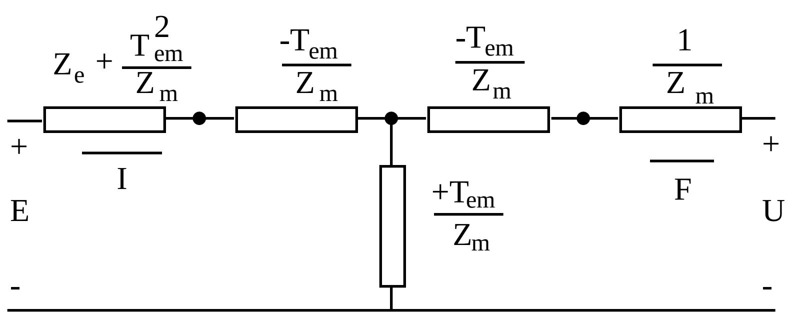

Figure 3. T network for mobility analog of the mechanical system

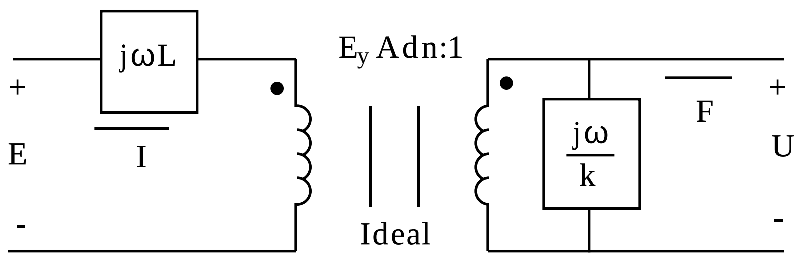

Figure 4. Equivalent circuit for magnetostrictive coupling

The equivalent circuit of figure 4 can also be constructed using a dependent voltage source in series with an inductor, as shown in figure 5. The dependent voltage source is proportional to the velocity (the proportionality being defined by the "turns ratio" of figure 4), or rate of strain, of the Terfenol rod. It should be emphasized that the derivation of the coupling equations presumed that the transducer was operating in a frequency range where its dynamics were stiffness dominated, i.e. it behaves like a linear spring. It should also be noted that a resistor has been included in figure 5. The resistor accounts for D.C. resistance in the coil.

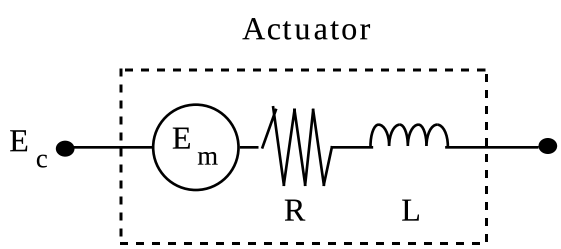

Fig. 5. Equivalent Electrical Circuit Model

To better understand the model, consider an actuator which is constrained from moving, or more precisely, a rod which is prevented from straining. In this case, the impedance is just that of a solenoid, a purely inductive load, and the velocity term disappears. Now suppose the open circuit voltage is measured when the rod is subject to a mechanical stress. In this case the transducer is a sensor, there is no driving voltage source, and the model of figure 5 reduces to the single voltage source E_m, where E_m represents the voltage due to magnetostriction.

Returning to the bridge circuit of figure 2, it is now possible to fill in the transducer block with its equivalent electrical representation. Using the equivalent electrical model, the bridge can now be redrawn as shown in Figure 6.

Solving the circuit of figure 6 for the voltage across R_4 yields the following expression for E_1 in terms of Laplace transformed impedance values:

$$E_1(s) = \frac{R_4 E_c(s)}{(R_4 + R_1) + L_1 s} + \frac{R_4 E_m(s)}{(R_4 + R_1) + L_1 s} \tag{19}$$

Similarly, solving for the voltage across R_3 yields the following expression for E_2:

$$E_2(s) = \frac{R_3 E_c(s)}{(R_3 + R_2) + L_2 s} \tag{20}$$

As was stated previously, the difference between voltages E_1 and E_2 should yield a signal proportional to the rate of strain induced in the Terfenol rod. Thus, the following expression is written for the differential voltage:

$$E_1(s) - E_2(s) = \frac{R_4 V_m(s)}{(R_4 + R_1) + L_1 s} + \left| \frac{R_4 E_c(s)}{(R_4 + R_1) + L_1 s} - \frac{R_3 E_c(s)}{(R_3 + R_2) + L_2 s} \right| \tag{21}$$

If R_3 and R_4 have the same value and $L_1/(R1+R4)$ is equal to $L_2/(R3+R2)$ then the equation for the differential voltage across the bridge reduces to the following:

$$E_{sensor}(s) = \frac{R_4 E_m(s)}{(R_4 + R_1) + L_1 s} \tag{22}$$

Equation (22) reveals that the bridge circuit behaves like a first order filter. Thus, for frequencies much less than $L_1/(R_4+R_1)$, the differential voltage will be proportional to E_m, and the signal will be proportional to the rate of strain. However, for frequencies much greater than the cutoff frequency, the circuit effectively integrates

E_m and yields a signal proportional to strain instead of rate of strain.

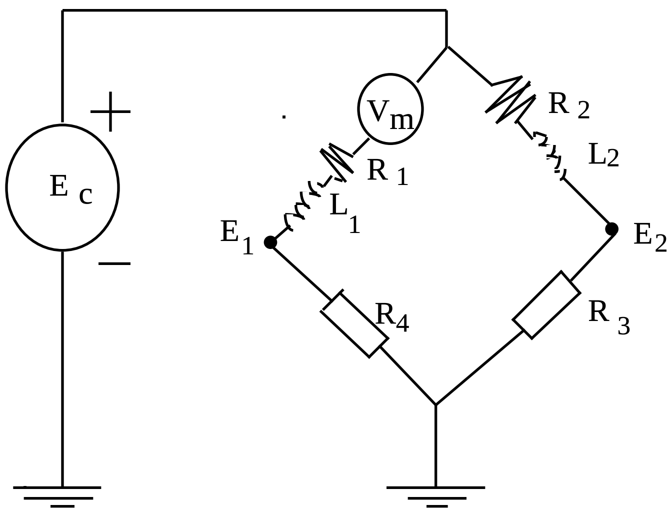

Fig. 6. Bridge Circuit Design for Self-Sensing Magnetostrictive Actuator

4. MOTIONAL IMPEDANCE

The electrical driving-point impedance at the transducer terminals is defined as the complex ratio of the voltage across the terminal pair to the current entering and leaving the pair of terminals, when all other electromotive forces and current sources are suppressed (Hunt, 1982). Thus, solving equations (5) and (6) for current I in terms of voltage E with F=0 leads to the following general expression for the driving point electrical impedance of an electromechanical transducer:

$$Z_{ee} \equiv \left(\frac{E}{I}\right)_{F=0} = Z_e + \frac{-T_{em} T_{me}}{Z_m} \tag{23}$$

Inspection of equation (23) shows that the driving point electrical impedance is composed of two terms: Z_e the blocked electrical impedance and a second term made up of the transduction coefficients, T_{me} and T_{em}, and the mechanical impedance, Z_m. The term containing the transduction coefficients is often referred to as the motional impedance, Z_{mot}, of an electromechanical device. Thus, the total driving point electrical impedance is the sum of the blocked and motional impedances. Physically, the equation states that even in the absence of an applied external force, the electrical impedance of an electromechanical transducer will be modified as a result of the motion of its mechanical component.

The motional impedance, Z_{mot}, can also be written as the product of a constant and the mechanical admittance, y_m, as follows:

$$Z_{mot} \equiv \frac{-T_{em}T_{me}}{Z_m} = (\text{const})(y_m) \tag{24}$$

where y_m is the reciprocal of Z_m. Thought of in this manner, one expects the contribution of the motional impedance to be slight for low frequencies. Low frequencies in this case are those that are well below the first mechanical resonance (a rule of thumb being at least a factor of ten). For instance, consider a single degree of freedom mechanical system of mass, m, stiffness, k, and damping constant, c, whose dynamics are described by the following admittance:

$$y_m = \frac{j\omega}{(k - m\omega^2) + (jc\omega)} \tag{25}$$

From equation (25) it can be shown that the admittance goes to zero as frequency does. Thus, the driving point electrical impedance approximates the blocked impedance for excitations well below the first mechanical resonance.

In the case of the magnetostrictive actuator, in the absence of an external load, the mechanical component is a compressively loaded Terfenol rod, and a plot of the driving point electrical impedance versus frequency should follow a curve that matches the blocked electrical impedance (inductive load) for frequencies well below the rod's first resonance.

5. EXPERIMENTAL MEASUREMENTS OF BLOCKED ELECTRICAL IMPEDANCE

As a first step in evaluating the validity of the above models and subsequent derivations, an experiment was conducted to measure the "blocked" electrical impedance of a prototype magnetostrictive transducer. The experimental set up was as illustrated in figure 7. The transducer was blocked by placing it in a vice like apparatus and the impedance measured as the ratio of the voltage to current in the frequency domain. Current was measured as the voltage drop across the .46 ohm series resistor, R, of figure 7.

Impedance data was taken using single frequency excitations at various frequencies between 20 Hz and 8 kHz. The resistance and reactance were measured at each frequency for a variety of power amplifier settings. The amplifier settings were varied to reveal non-linearities which might exist. One set of these results is presented in figure 8.

As is evident in figure 8, the reactance is a strong function of rms drive current amplitude (a curve fit of this data indicated a roughly square root relationship). Qualitatively, similar curves were found at all frequencies tested with each data set showing a tendency for reactance to vary with the rms current.

The real portion of the complex impedance exhibited a dependence on rms drive current that became more pronounced at higher frequencies. Figure 9 is a plot of the real part of the complex impedance as a function of rms drive current at an excitation frequency of 8 kHz.

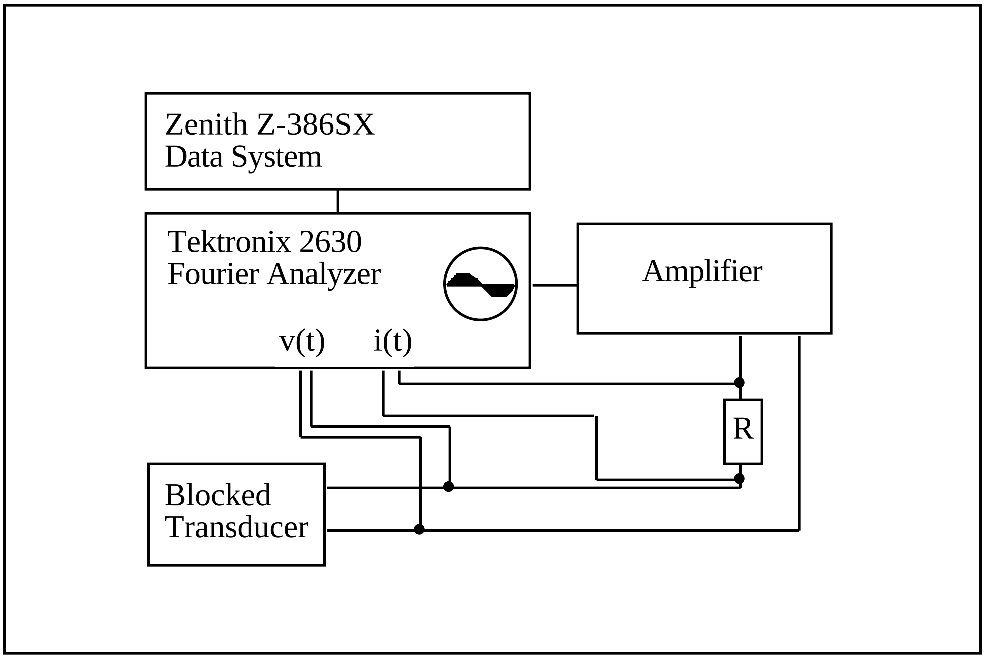

Fig. 7. Blocked Impedance Experimental Set Up

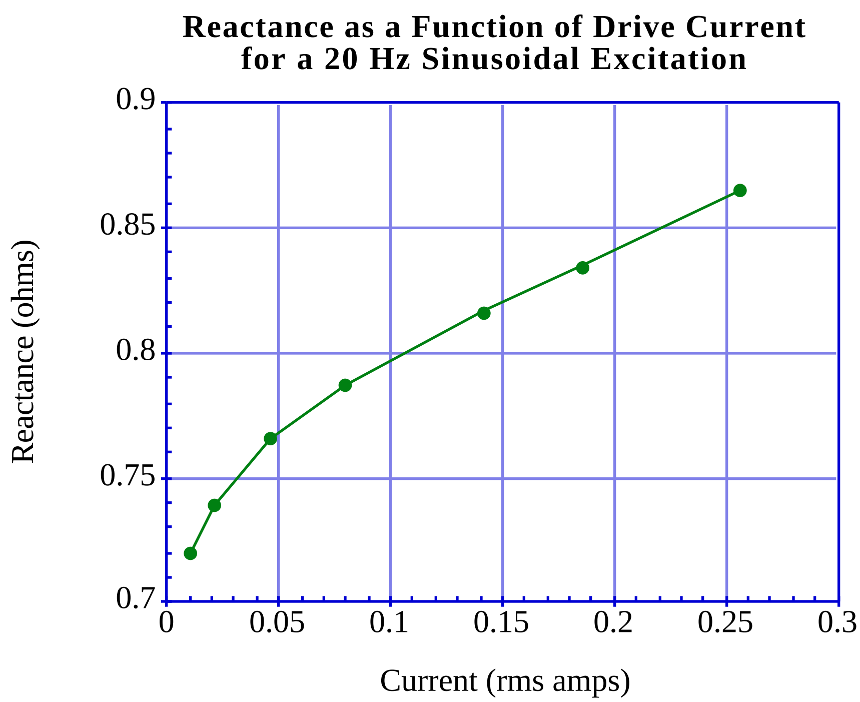

Fig. 8. The Imaginary part of the Complex Impedance for a "Blocked" Terfenol-D Transducer at 20 Hz.

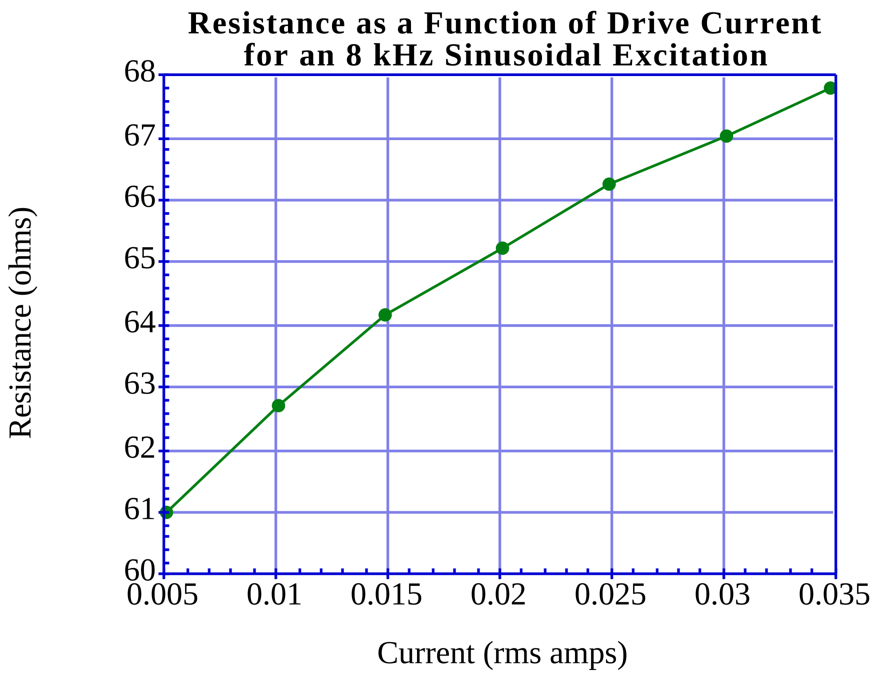

Fig. 9. The Real part of the Complex Impedance for a "Blocked" Terfenol-D Transducer at 8000 Hz.

6. EXPERIMENTAL MEASUREMENTS OF SELF-SENSING

The results of the blocked impedance measurements indicated the linear assumptions of the model were wrong. However, analogous non-linearities have been observed in piezoelectric transducers and self-sensing actuators have been fashioned from these devices (Dosch, 1992, Hagwood, 1991). Thus, a variety of experiments were carried out to investigate whether a self-sensing transducer might still be achieved, and as a first step, a simple version of the bridge circuit shown in figure 6 was built as illustrated in figure 10.

Note, that the 10 ohm resistors in figure 10 correspond to R3 and R4 and that the variable inductor corresponds to the combination of R2 and L2 in figure 6. Hence, the variable inductor mimics the blocked electrical impedance of the transducer. As such, a wound wire coil essentially identical to the solenoid in the actuator was first selected for this circuit element. The impedance of this coil was adjusted by varying the position of a steel rod in the core.

A mass was affixed to the top end of the self-sensing transducer. The transducer's bottom was mounted on a shaker table. Output of the bridge circuit was fedback through an amplifier. It was assumed that the output of the bridge circuit was proportional to the velocity of the affixed mass, and that feedback of the signal would correspond to velocity feedback control. The acceleration of the mass was monitored in response to input vibration at the actuator base. With this crude system it was possible to lower the acceleration response of the affixed mass by approximately 6 decibels using the feedback control (the accelerometer signal was observed to be reduced by a factor of two on an oscilliscope). The controller was "tuned" qualitatively by selecting amplifier gains and then manually adjusting the inductance in the bridge circuit through positioning of the steel rod until the greatest reduction in transmitted vibration was observed. This procedure worked best at the mass loaded actuator's axial resonance.

Next, various means were attempted to bring the bridge into balance for the case when the transducer was restrained from motion (blocked). When the transducer is blocked (i.e., clamped in a vise and no base excitation), the output of the bridge for an applied control voltage should be nearly zero; because, in order to achieve true self-sensing the transducer's blocked impedance and that of the variable inductor must be the same. The procedure for balancing the bridge was as follows. The feedback loop was open circuited and a single frequency, sinusoidal control voltage, E_C, was applied to the input terminals of the bridge circuit and the bridge output E_O was monitored. A voltage signal, E_1, proportional to the voltage drop across the 10.01 ohm resistor was also monitored. While monitoring these signals, the variable impedance leg of the bridge was adjusted to minimize E_0. With the bridge tentatively zeroed in this fashion, the autospectrums of each of the measured voltages were recorded. The difference in amplitude between E_1 and E_0 was used to measure the bridge common mode rejection. A trial and error approach was used to maximize common mode rejection for a single frequency excitation of 2.15 kHz. The frequency 2.15 kHz was selected because it corresponded to the axial resonance of the mass loaded transducer in the original experiment. Ultimately, the goal was to balance the bridge for the blocked condition, attach the mass, and then observe the bridge output when the transducer was free to vibrate.

The single coil with a steel rod used in the first experiment proved ineffectual for balancing the bridge and was replaced by another Terfenol actuator. It was reasoned that the impedance characteristic of an essentially identical transducer should bring the bridge into balance, since presumably the two Terfenol actuators would behave in similar non-linear fashions. Each transducer's impedance was measured for a fixed frequency and current amplitude. By adjusting the pre-stress, (Terfenol actuators typically have an adjustable compressive pre-stress) and using a trim pot to adjust resistance, it was possible to make the two transducers have the same apparent impedance. However, they differed enough in their impedances that a residual signal on the order of millivolts was present across the bridge when excited by a control signal on the order of volts. This residual signal was on the same order of magnitude as signals produced by mechanical loading (a rap on the housing) of one of the transducers while in the bridge configuration. Thus, for this experiment, the bracketed terms of equation (21) were of the same size as the magnetostrictive voltage term, and the bridge was unsuccessful at providing a signal purely proportional to mechanically induced strain. Furthermore, if drive current was increased (amplifier gain turned up), the bridge quickly went out of balance and the differential voltage was merely an attenuated version of the control voltage. As a result, no attempt at self-sensing was made with this arrangement.

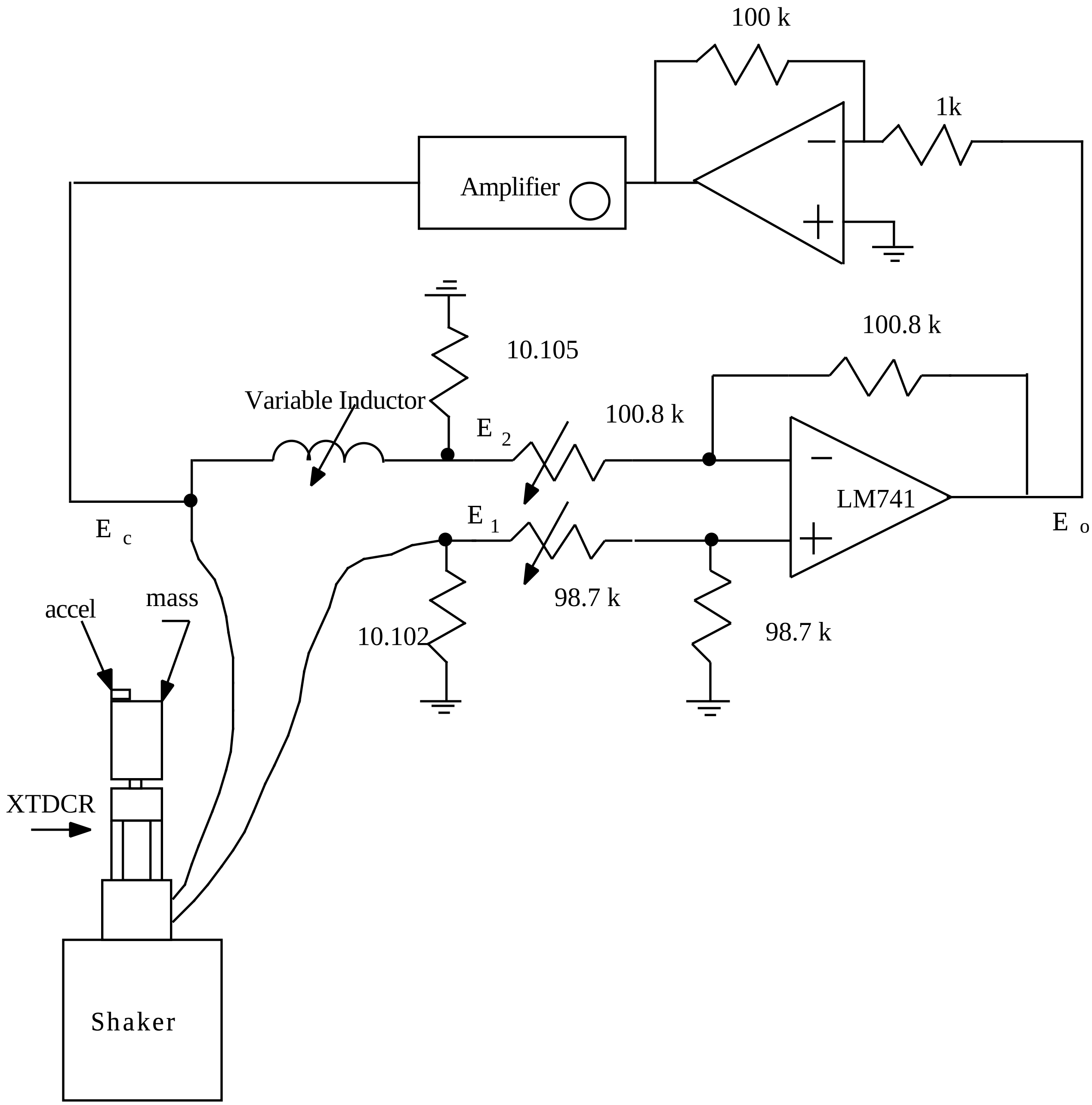

Fig. 10. Self-sensing Experimental Set Up

A final attempt at self-sensing was carried out using another variable inductor device to mimic the transducer's blocked impedance. In this case, a pair of wound wire coils connected in series were substituted into the passive leg of the bridge to try and balance with the transducer. Each coil had a steel core that could be positioned to vary the coil impedance. This arrangement succeeded in acheiving a difference of 50 dB's between E_1 and E_o for an excitation current level of approximately 2 mA in the passive leg of the bridge.

After the bridge was balanced for a single frequency and amplitude of control voltage, pseudo random sinusoidal excitation was applied to the bridge. This experiment was performed to determine the bandwidth that could be expected from the bridge circuit given that the variable impedance element did not have the same frequency response as the transducer blocked impedance. Once again, E_o and E_1 were recorded and autospectrums of these signals indicated that the bridge had "good" common mode rejection for a very narrow bandwidth (±50 Hz) about the 2.15 kHz excitation frequency.

For the self-sensing experiment, a mass load was added to the system. The additional mass lowered the first resonant mode of the transducer. Thus, with the additional mass load, the transducer impedance no longer approximated the blocked impedance. The bridge that had been balanced for a frequency of 2.15 kHz now went out of balance for frequencies near the new system resonance. Pseudo-random excitation was applied as a control voltage and the bridge output recorded. The resulting autospectrum is plotted in figure 11 and compared with the resulting acceleration response. A clearly discernable peak in the self-sensed signal is observed for a frequency of 2.2 kHz that matches that occuring in the accelerometer.

Finally, the loop was closed, and the original self-sensing feedback control experiment was repeated. The acceleration response to base excitation, with and without control, is shown in figure 12. Simple proportional feed back control using the self-sensed signal appears to have lowered the system resonance and significantly reduced the response.

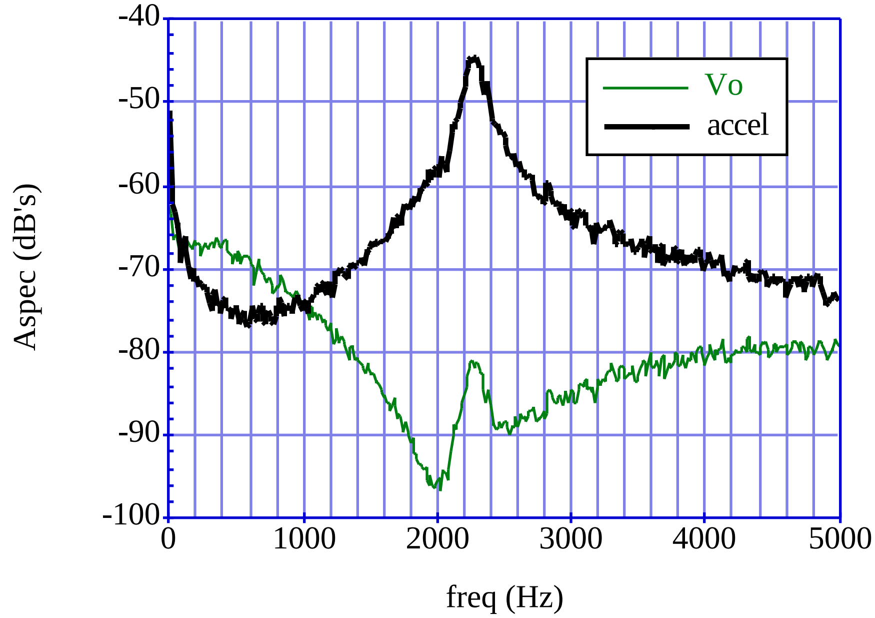

Fig. 11. Self-sensing output for broadband excitation of mass loaded actuator compared with mass acceleration

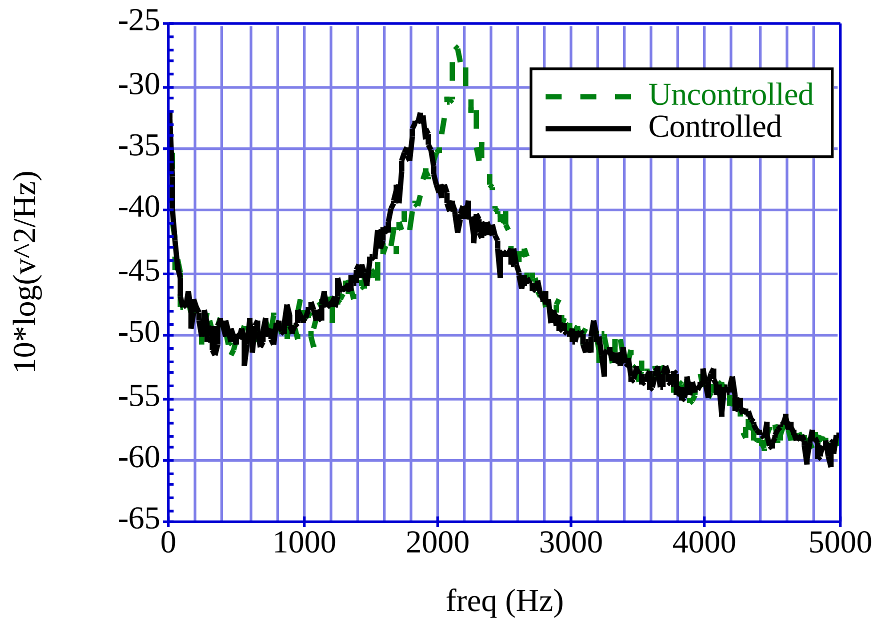

Fig. 12. Self-sensing vibration control for broad band base excitation.

7. DISCUSSION OF EXPERIMENTAL RESULTS

Care must be exercised in drawing conclusions from the blocked electrical data about the relationship between impedance and current amplitude. The trends shown are for rms values of sinusoidally oscillating drive currents, thus it appears that each data point represents an average impedance. If impedance is truly a function of current amplitude, as the data would indicate, then a time varying input current must produce a time varying impedance.

The "blocked" electrical impedance experiments performed show impedance is a non-linear function of the average drive current amplitude. This is explained by the assumption of a constant value for the permeability, μ, of the material. Recall from equation (10) that the blocked impedance (the coefficients multiplying di/dt) includes the permeability. The permeability of Terfenol is approximated as the slope of its magnetization curve for a constant applied mechanical stress. However, magnetization curves for ferrous materials such as Terfenol are not linear and exhibit a marked hysteretic character. A qualitative example of a normal hysteresis loop for a ferrous material is shown in figure 13, where the width of the loop has been exagerrated for the purposes of illustration. Minor hysteresis loops, also illustrated in figure 13, are traced out if the variation in magnetic field intensity is reversed before reaching either limit of the major loop. Minor loops are typically lense shaped, and have an incremental permeability approximated by the slope of their major axis. Thus, the permeability of a ferrous material like Terfenol is a constant only in a time averaged sense.

For dynamic applications, Terfenol actuators are typically magnetically biased by a fixed magnetic field, H_0, then are driven by an oscillating current in the solenoid which sets up a cyclic variation in magnetic field intensity about H_0. Magnetically, the actuator operates around a minor hysteresis loop. Apparently the shape and orientation of this minor loop depends on the amplitude of the drive current (Hall, 1993), and gives rise to the variation in impedance observed in figures 8 and 9.

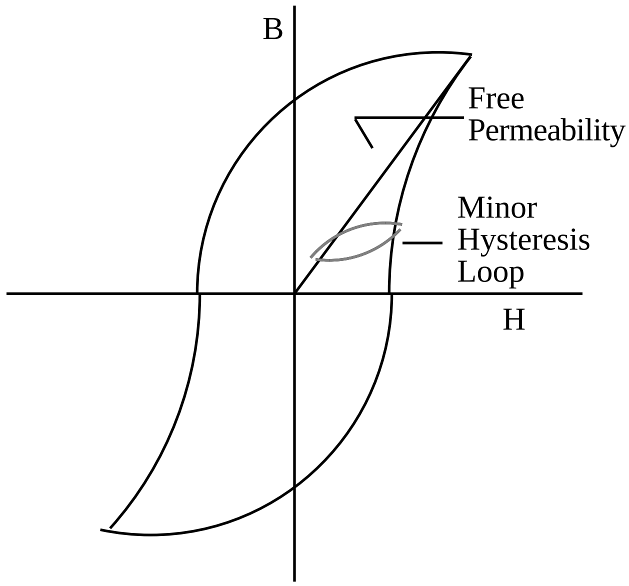

Fig. 13. Normal Hysteresis Loop

It can be argued that the blocked impedance experiment did not measure a true "blocked" impedance since the actuator could in fact move. However, at low frequencies (i.e. a decade below the first resonant mode of the rod; for this device up to approximately 1000 Hz) there should be little or no difference between impedance measurements, blocked or otherwise, and at 20 Hz the data should have been a reasonable approximation of the blocked condition. Nonetheless, even if the experiment had measured blocked impedance, non-linear electromechanical coupling would still present problems for magnetostrictive self-sensing actuation.

Consider the driving point electrical impedance shown in equation (23). The motional impedance term includes the transduction coefficients T_{me} and T_{em} , and from equation (12), T_{em} may be written as:

$$T_{em} = Nd\frac{AE_y}{l} \tag{26}$$

As presented above, the transduction coefficient includes the magnetostrictive constant, d, which is taken as a material property and is the slope of the H vs ε curve. This curve has hysteresis, and, as might be expected from the previous discussion of permeability, experiments have shown that the constant d is also a function of drive current (Hall, 1993). The implication is that it is impossible to linearly decouple mechanical from electrical effects. Self-sensing electromechanical actuators monitor the variation in motional impedance and use this as an indication of the motion of the mechanical system. In this application, motional impedance varies not only as a function of the mechanical system, but as a function of the electromagnetic system, and it appears difficult to differentiate between the two effects.

The results of the self-sensing experiments did demonstrate the potential of the concept, however. Figure 11 shows that for certain combinations of electrical and mechanical loading the motional impedance is dominated by mechanical effects, and that for this narrow set of operating parameters the non-linear electromagnetic effects are small enough to be ignored. Figure 12 is evidence that the self-sensed signal obtained can be used effectively for active vibration control.

8. CONCLUSIONS

A method for achieving self-sensing actuation for a magnetostrictive transducer has been demonstrated. Experimental data have been presented that show a bridge circuit can be constructed to extract information about the actuator motion. The results suggest that further refinement of the design will be required to account for non-linear behavior that at present limits the performance to a narrow range of frequencies about the mechanical system resonance. Research is required to more clearly define the operating regimes and parameters where nonlinear effects must be considered. It remains to be determined if a blocked impedance that is independent of drive current amplitude can be measured. Further study of the transducer's motional impedance should also be conducted to establish to what extent nonlinearity effects this parameter. A nonlinear model should be developed if possible. A time domain model of the current to voltage relationship for this device will be required. Using the nonlinear time domain model, it may be possible to construct an adaptive bridge circuit capable of improved self-sensing.

9. ACKNOWLEDGMENTS

The authors wish to express our appreciation to Edge Technologies, Inc., for their assistance in working with Terfenol-D and as an information source in general. David L. Hall's contribution to the restating of the transduction equations is also acknowledged and appreciated. This research was supported in part by the NASA / Iowa Space Grant Consortium and the National Science Foundation (grant # MSS 9212065).

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11. NOMENCLATURE

A	rod cross sectional area
B_j	flux density
d_{ji}	piezomagnetic strain constant

$e(t)$ voltage

E Laplace transformed voltage

E_y Young's modulus

F Laplace transformed force

H_i magnetic field intensity

$i(t)$ current

I Laplace transformed electrical current

k equivalent stiffness of an axially loaded rod

l solenoid length

L electrical inductance

n number of turns in a solenoid

N turns times solenoid length

R electrical resistance

S_j strain

s^H_{ji} compliance for constant applied magnetic field

T_i mechanical stress

T_{em} transduction coefficient

T_{me} transduction coefficient

$u(t)$ velocity

U Laplace transformed velocity

Z_e blocked electrical impedance

Z_m mechanical impedance

Z_{ee} driving point electrical impedance

Z_{mot} motional impedance

φ magnetic flux

μ^T permeability for constant applied stress

μ^σ permeability for constant applied uniaxial stress

ε uniaxial strain

σ uniaxial stress