Measured Terfenol-D material properties under varied applied magnetic field levels

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ABSTRACT

An experimental approach is used to identify Terfenol-D material properties under magnetic bias and mechanical prestress conditions typical of transducer applications for the magnetostrictive material Terfenol-D. The approach is based on low signal transduction models, a mechanical model of the test transducer, and on the theory of vector impedance and admittance analysis. The material properties being investigated, measured directly or calculated from measured quantities, are: two Young's moduli, magnetomechanical coupling factor (or "figure of merit" of the material), linear coupling coefficient or axial strain coefficient (d33), and two magnetic permeabilities. Electrical impedance and admittance and acceleration per unit current complex functions are measured at frequencies from 100 Hz to 5 kHz using a swept sine excitation at five applied magnetic field levels. Ten Terfenol-D samples are used in randomized performance tests to obtain the preliminary material property information that is presented. Of these ten rods, two were used in randomized performance repeatability tests for which data is also presented. These data sets demonstrate the dependence of material properties on applied magnetic field levels, and provide a preliminary assessment of the variability in material properties given known operating conditions.

Keywords: Terfenol-D, magnetostriction, linear transduction, vector complex impedance, vector complex admittance, dynamic material properties, transducer, magnetostrictive transducer, three parameter method

1. BACKGROUND

Terfenol-D is an alloy of iron, terbium and dysprosium that has the property of being magnetostrictive, that is to say, it strains under the application of a magnetic field. Terfenol-D is used in transducers to generate oscillatory motion and forces at frequencies from DC to over 20 kHz. Efficient design of Terfenol-D transducers requires knowledge of the dependence of Terfenol-D material properties on a variety of transducer operating parameters, including initial mechanical prestress, initial magnetic bias, applied magnetic field or drive level, and temperature. Transducer models that incorporate the influence of all operating parameters simultaneously are not currently available, in large part because models are not yet available of the functional dependence of basic material properties such as permeability and elastic modulus on operating conditions.

Prior studies have suggested a strong dependence of Terfenol-D material properties upon operating conditions.[1] References 1-5 among others present experimental results that show some of material properties will vary with operating conditions by as much as 25%. Some analytical models are available that demonstrate certain aspects of this behavior are to be expected due to the nature of magnetostriction.[2] For the transducer designer, it is important to be able to understand such trends, and to recognize which trends are predictable with various operating conditions. Transducer designers should also be aware of any potential for variability in trends between Terfenol-D samples and between tests of the same sample under the same operating conditions. Obtaining information on trends requires the ability to obtain a statistically significant data base on material properties in controlled operating conditions.

Although much work has been done on characterizing properties of single crystals of magnetostrictive materials, only limited information is available on Terfenol-D material property behavior as used in transducers; with an initial magnetic bias, an initial mechanical prestress, and a dynamic load. In addition, it is difficult to use material property information existing in the literature to draw conclusions about material property trends as from reference to reference, basic operating conditions such as magnetic circuit, initial magnetic bias and mechanical prestress vary. This project was undertaken with the goal of identifying trends in the functional dependence of material properties on changes in operating conditions in a controlled environment. This paper presents preliminary data from this project on material properties of engineering interest (i.e. for use in transducer design) under varied applied magnetic fields, in transducers of fixed design, initial mechanical prestress, load, temperature and initial magnetic bias; transducer features which a designer can control. The importance of realizing the ability to quantify Terfenol-D material properties *in a transducer* stems from the desire to understand the material property trends and variability when used under a compressive prestress as part of a typical transducer magnetic circuit. The data presented are part of a larger on going study in which additional operating parameters (mechanical load, temperature and transducer design) are to be varied. These results should aid in more realistic modeling and design of transducers and enhance the ability of designers to optimize transducer performance for specific dynamic applications.

2. DESCRIPTION OF EXPERIMENT

2.1. Experimental factors

The preliminary results presented in this paper are from an experimental investigation of ten samples of quarter inch diameter, two inch long Terfenol-D material manufactured by the Free Stand Zone Melt method. These samples exhibited nominal strains of 1000 microstrain under a 1.0 ksi prestress at a DC magnetic field of 500 Oe. The samples were tested in transducers operated at five applied magnetic field levels. The Terfenol-D samples and the applied magnetic field levels are the two experimental factors intentionally varied in this study. To the extent possible, efforts were made to avoid variations in the additional experimental factors as summarized below.

Four transducers were built for the purpose of this testing, all of them made to the same specifications following an original design.[2] The transducer base mass is 3.0 Kg, and its dynamic load 74.25 grams, providing a reasonable approximation of its mechanical dynamics to be made with a fixed-free single degree of freedom linear spring-mass model. The Terfenol-D sample is surrounded by a cylindrical wound solenoid, consisting of a 12 layer driving coil and an innermost single-layer sensing or pick-up coil. The solenoid has a nominal length of 2.20 inches and is made out of AWG 26 magnet wire. A Gauss-Meter (Bell 4048) was used to map the magnetic field per unit current along the central axis of the drive coil in each transducer, and a weighted average (the area under the curve "magnetic field amplitude vs. position" divided by the total length of the coil), was used to calibrate the drive current needed in each transducer to obtain the desired applied magnetic field levels. A slit Alnico V cylindrical magnet surrounds the solenoid and accounts for part of the total magnetic bias acting upon the Terfenol-D rod. Table 1 indicates both the coil ratings and magnetization of the permanent magnets in each of the four transducers. Four transducers are used in this study to aid in determination of whether or not the transducers themselves will act as an experimental factor influencing material property trends. Insufficient data have been collected at this time, however, for formal statistical evaluation of transducers as an experimental factor.

Table 1. Transducer coil rating and DC magnetization due to Alnico V permanent magnet.

Transducer	Drive Coil Rating (Oe/A)	DC magnetization (Oe)
1	297	197
2	287	230
3	300	213
4	297	189

Transducer mechanical prestress level, mass loading, temperature, and initial magnetic bias are factors that influence Terfenol-D material properties. For this specific investigation, however, they are set to fixed (measured) values at the start of data collection for each measurement, and are not varied as experimental factors of this study.

The prestress value is kept constant during testing at a value of 1.0 ksi. A transducer calibration was obtained using an MTS compression test to relate displacement at the output of the transducer and stress (force) over the output push rod of the transducer. The measured stiffness of this prestress mechanism was 1.66×10^6 N/m in all transducers. A dial indicator fixture is then used prior to each test to ensure that the position of the prestress bolt in the base of the transducer is set to obtain a DC displacement in the transducer output corresponding to a 1.0 ksi compressive stress acting on the rod.

Tests were run at room temperature (20 to 30 °C). Because some heating of the Terfenol-D rod is produced by ohmic heating of the drive coil, sufficient time was allowed in between tests to ensure that the transducer returned to room temperature at the beginning of each test. A steel cylinder with a mass of 63 grams (equal to approximately four times that of the Terfenol-D rod) was threaded to the transducer's output push rod and provided a mass loading of the transducer. With the addition of the mass of transducer moving components, an effective dynamic mass of 74.25 grams was the transducer's dynamic mass load. (Future experiments are planned to complete an analysis of sensitivity with respect to temperature and mass loading.)

For this study, the initial magnetic bias, H_o, was selected so that a symmetric or balanced strain-applied field relationship existed when operating the transducer to achieve outputs of ±25 microns (equivalent to ±500 microstrain for a two inch long rod). The value of H_o needed to obtain a symmetric strain-applied field relationship was determined for each of the ten Terfenol-D samples in a transducer in which the permanent magnet had been demagnetized. Figure 1 shows the magnetic bias H_o that satisfies the above condition in a typical strain versus applied current curve. A current of approximately ±1.07 A, corresponding to an applied field of ±318 Oe at either side of the initial magnetic bias H_o=318 Oe produces a displacement of ±25 microns at either side of the initial transducer output position (zero displacement). Experiments to produce curves like that of Figure 1 were run for the 10 Terfenol-D samples in one transducer. The transducer's permanent magnets were capable of providing approximately two thirds of the desired magnetic bias. Current from a DC power supply was used to provide the precise levels of additional magnetic field needed for each of the ten rods. As the permanent magnets used in the four test transducers had slightly different magnetization levels (between 189 and 230 Oe) the measured magnetization value of each transducer's magnet was used to calculate the required additional DC current for each rod in each transducer. In summary, each rod has a magnetic bias point H_o associated with it, that is assumed to be independent of the transducer used to run the test. The necessary DC bias current for each of the ten rods in each of the four transducers, I(rod,transducer), is calculated from the formula:

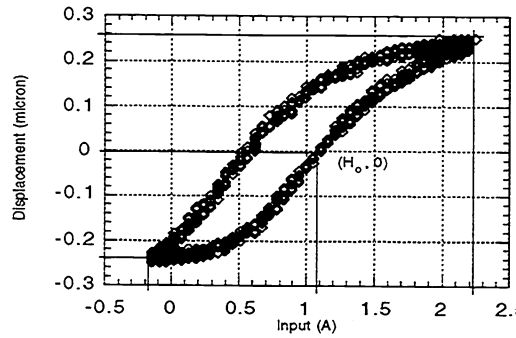


Figure 1. Displacement vs. applied current curve. Excitation at 0.6 Hz. For rod 7 in transducer 4, $H_o \propto 1.07$ A.

$$I\,(\text{rod, transducer}) = \frac{H_0\,(\text{rod}) - M\,(\text{transducer})}{R\,(\text{transducer})} \tag{1}$$

where H_o (rod), Oe, is the magnetic bias needed for symmetric ±500 microstrain, M (transducer), Oe, is the magnetization level of the transducer's Alnico V permanent magnet, and R (transducer), Oe/A, is the rating of the transducer's drive coil. Table 2 summarizes the above mentioned procedures.

Table 2. Row 1 & 2: Rod number and corresponding serial number. Row 3: H_o(rod), DC magnetic field bias needed to obtain symmetric ±500 microstrain. Row 4-7: DC current (in ampere) needed to supplement transducer's permanent magnet field to obtain DC magnetic bias of row 3. Nominal transducer coil ratings: 300 Oe/A.

Rod	1	2	3	4	5	6	7	8	9	10
Serial #	94-248A	94-224C	94-224E	94-237E	94-112A	94-224A	94-248E	94-250E	94-250A	94-250C
DC bias, H_o (Oe)	315	345	315	315	315	306	321	300	321	318
I (r,1), (M(1)=197 Oe)	.39	.49	.39	.39	.39	.36	.41	.34	.41	.40
I (r,2), (M(2)=230 Oe)	.25	.35	.25	.25	.25	.22	.27	.20	.27	.26
I (r,3), (M(3)=213 Oe)	.34	.44	.34	.34	.34	.31	.36	.29	.36	.35
I (r,4), (M(4)=189 Oe)	.41	.51	.41	.41	.41	.38	.43	.36	.43	.42

Applied AC magnetic field level is the only experimental factor, other that the ten Terfenol-D samples themselves, to be intentionally varied at this time in this study. (Recall that although four transducers are used, it is hoped that they will not interact with the Terfenol-D and drive levels.) Tests were conducted at five applied magnetic field levels: 2, 5, 10, 20 and 50 Oe. The levels were selected to range from a low magnetic field to the maximum allowable magnetic field for safe operation of this transducer design at resonance given the stated operating conditions (mechanical prestress, temperature, dynamic load, etc.). The maximum safe field at resonance had to be determined experimentally. "Safe" is based on that it is desirable to operate Terfenol-D under a compressive stress at all times to avoid fracture and/or chipping of the material. Newton's second law (F= ma) can be used to show that for a mechanical prestress setting of 1.0 ksi and a dynamic transducer load of 74.25 grams, accelerations at the transducer output in excess of 298 g's will correspond to an output force that exceeds the prestress. The axial compressive force that produces a 1.0 ksi axial compressive stress in a quarter inch diameter rod is 218 N (49 lb_f), hence for a total mass of 74.25 gm the maximum allowable acceleration is 2922 m/s^2, or 298 g's. When this acceleration is measured at the transducer output, the transducer load is accelerating away from the rod; the rod is about to be impacted by the returning dynamic load; even temporary separation of the Terfenol-D rod and transducer dynamic load may result in chipping or other forms of damage to the rod. A 10% safety factor was imposed, for a maximum allowable acceleration of 268 g's. A randomly selected Terfenol-D sample was then driven at resonance in a randomly selected transducer at increasing applied field levels. An acceleration of 270 g's was reached at a field of 70 Oe, which in turn became the maximum "safe" drive level for running the transducer under the stated operating conditions.

2.2. Instrumentation

A swept sinusoidal current of constant amplitude from 100 Hz to 5 kHz was desired as input to the transducer drive coil to produce constant applied magnetic field levels to frequencies above the first axial transducer resonance. Appropriate AC current levels were determined based on the measured coil ratings, R(transducer). A summing circuit was used to add the DC bias current and AC drive current, and the combined signal sent to the transducer.

Difficulties in achieving constant current to the transducer were introduced by both that the transducer's coil acts as an inductive load and that Terfenol-D permeability and hence complex inductance varies with frequency quite significantly near resonance.[2] To maintain constant current to this load, the voltage to the transducer was varied with frequency. This was implemented using a drive signal to the coil generated with either a 2642A or a 2630 Tektronix Personal Fourier Analyzer, that was in turn amplified in either a 7780 Techron Power Amplifier fitted with a built-in current control module or a Techron 7520 fitted with a optional current control module. The amplifiers were operated in current control mode, as opposed to voltage control mode. The extent to which the amplifiers complied with the requisite of output *current* following both the shape and magnitude of the input voltage over all the frequency range is a troublesome issue, as the transducer proved to be a difficult load for both current control modules near transducer resonance. To the extent possible, efforts were made to ensure minimum variability in the amplitude of the drive current fed into the transducer over the entire frequency range. However, as illustrated by Figure 2, deviations from the mean of no more than ±5% were achievable except just above and below electrical resonance.

The Tektronix Personal Fourier Analyzers cited above were used in swept sine mode of operation to collect data on transducer output acceleration, voltage and current in the drive coil, and voltage across the sensing coil. The options in this mode of analyzer operation allow the frequency range to be broken into up to twenty spans of varied frequency increments, bandwidth, and dynamic range. Figure 2 reflects a typical setup used to obtain desired resolution at low frequencies and near resonance involved increasing the transducer excitation frequency in increments of 25 Hz from 100-1000 Hz and from 2000-4000 Hz, with increments of 100 Hz from 1000-2000 and 4000-5000 Hz. Note that the span breaks are evident in Figure 2, and that the output signal to the amplifier was scaled for each span to aid in obtaining the desired mean current over each span. Ten measurements, zoomed to ±20 Hz around each excitation frequency, were used in calculation of averaged frequency response functions (output autospectra over input/output cross spectra) from the measured data. The four time input signal auto spectra along with coherence frequency response functions of both voltages per unit current and acceleration per unit current were stored. (Note also that attention was paid to signal to noise ratios by adjusting analyzer full-scale voltage levels to maximize use of the input dynamic range in each channel for each span of each test of every rod.)

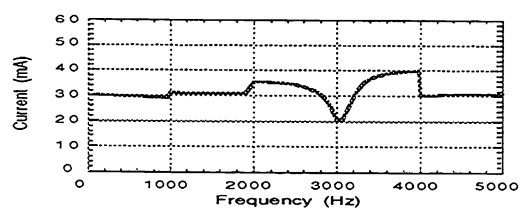


Figure 2. Influence of transducer as a dynamic load on current input to transducer versus frequency while trying to maintain a constant applied field of 10 Oe. (Test with rod 2 in transducer 1.)

Acceleration was measured with a 3 gram accelerometer (Kistler type 8694MI) and amplified by a Kistler 5134 Power Supply/Coupler. To obtain acceptable voltage levels for input to the signal analyzer, operational amplifier circuits were built and calibrated to step-down the constant current amplifier outputs for monitoring voltage and current to the drive coil and to amplify the voltage across the sensing coil.

2.3. Randomization

The experiment was designed with the randomization principle in mind. To minimize any bias in the data due to interaction between factors, it was necessary to assign rods and drive levels to transducers in a random manner. In addition, eight individuals were involved in conducting the tests; the testers may need to be recognized as a fourth experimental factor. Testers follow a detailed set of test procedures developed through an iterative process to standardize test procedures and minimize variability in results obtained by a team of eight different testers. Even with neglecting testers as an experimental factor, identifying the ten rods, the five drive levels, and the four transducers as the experimental factors requires two hundred tests to complete a full factorial test matrix representing all possible combinations of rods, transducers, and drive levels. If the transducers are similar enough to not act as a distinct experimental factor influencing material properties (as was the intent of their design) a matrix of fifty tests satisfies all rods being studied at all drive levels. As such, each combination of rod and drive level was tested with the transducers (as a third potential experimental factor) randomly assigned using a random number generator. This resulted in transducer #1 being assigned 14 tests; transducer #2, 11 tests; transducer #3, 14 tests; and transducer #4, 11 tests. Fifty tests were conducted in a random order by a random sequence of testers over a period of one half month.

2.4. Test-to-test repeatability

Replication tests were run using rods #1 and #5 at four drive levels (5, 10, 20, and 50 Oe) and randomly assigning one of the four transducers to each of the eight tests (random selection process involved pulling a number from one to four from a hat). (Current work includes a more complete study in which four randomly selected rods are tested at four drive levels with the four transducers randomly assigned using a Latin Square blocked experimental design, allowing for an improved analysis of statistical significance of the different factors.) Table 3 shows the two rods, four drive levels and corresponding transducers; each block represents a sequence of ten tests. The rod-transducer pairs were assembled and used at the same drive level for ten consecutive tests. (Theoretically, the only uncontrolled factor in these tests was time of day.) Special care was taken to avoid ohmic heating in the coil affecting the results; transducers sat idle during at least thirty minutes after each run, to ensure the entire transducer returned to room temperature before the next test of the sequence was run.

Table 3. Sets of ten tests were run for two Terfenol-D samples at four drive levels. Transducers were assigned randomly. Prestress was set at 1.0 ksi, temperature range was 20-30 °C.

Drive level	Rod # 1	Rod # 5
5 Oe	Transducer 1	Transducer 2
10 Oe	Transducer 1	Transducer 1
20 Oe	Transducer 4	Transducer 3
50 Oe	Transducer 4	Transducer 3

3. MODELING MATERIAL PROPERTIES

Models based on the principles of electroacoustic theory, low signal transduction models and a mechanical model of the test transducer are used to calculate Terfenol-D material properties from a number of measured parameters. Measured parameters used in calculations include: complex frequency response functions of acceleration per unit current in the drive coil, complex electrical impedance frequency response functions of pick-up coil voltage per unit current in the drive coil, mechanical prestress of the transducer, masses of the transducer base, of the rods, and of the transducer load, rod lengths and rod diameters.

The resonant frequency, f_r (and half power point frequencies, f_1 and f_2) are identified from Nyquist plots of the electrical impedance function using principles of electroacoustics.[6] This resonant frequency is used in a mechanical model of transducer at resonance[2] to calculate the mechanical linear rod stiffness, k_m^H :

$$k_m^H = (2\pi f_r)^2 \left(\frac{m_1 m_2}{m_1 + m_2} \right) - k_{mps} \tag{2}$$

where k_{mps} is the measured stiffness of the transducer prestress mechanism, m_1 is the mass of the transducer base, and m_2 is the sum of one third the mass of the Terfenol-D rod and the mass of the transducer load.

The linear rod stiffness is used in calculation of both the Young's modulus at constant applied field, E_y^H and the axial strain coefficient, q. E_y^H is calculated with:

$$E_y^H = \frac{L\, k_m^H}{\pi\left(\frac{D^2}{4}\right)} \tag{3}$$

where D and L are the measured rod diameter and length, respectively.

The axial strain coefficient, q, (also known as the d "constant" and the d_{33} linear coupling coefficient) is a measure of the strain per unit applied magnetic field and has units of strain per amp-turn per meter. IF hysteresis and nonlinearities in the data of Figure 1 were negligible, one could measure the slope of the displacement versus applied current data, back out transducer effects, and convert to appropriate units to provide an estimate of the axial strain coefficient. In fact, one practice for measuring q is to draw a straight line through the extreme of such data and to relate the slope of that line to q; neglecting that hysteresis and nonlinearities cause a line to be quite a poor fit of the data. To provide a better measure of q, the transducer for this study was designed so that it behaves approximately as a single degree of freedom fixed-free spring mass system. If one were measuring displacement per unit force (u/F), responses at frequencies up to approximately 10% of the first axial resonant frequency are in the stiffness controlled portion of the system dynamic response and have a value equal to the system's axial spring coefficient (k= F/u). An analogous theoretical development[6] shows that an average of the strain per unit applied field in this region is a reasonable approximation of the system's axial strain coefficient. Making the assumption that the applied magnetic field is linearly proportional to the drive current, H= n I (as quantified by the measured coil rating), where n= turns per unit length and taking into account that strain is change in length per unit length, q can be written as:

$$q = \frac{\varepsilon}{H}\left(1+\frac{k_{mps}}{k_m^H}\right) = \frac{u}{n\ I\ L}\left(1+\frac{m_2}{m_1}\right)\left(1+\frac{k_{mps}}{k_m^H}\right) \tag{4}$$

with u/I the displacement at the free end of the rod per amp determined from the measured acceleration per current divided by circular frequency squared average over frequencies below 10% of resonance (and L nominal rod length). Two additional terms (both of magnitudes close to one) are included to correct for modeling approximations involving the measurements taking place in a transducer, as opposed to on a bare rod. The stiffness term corrects for the effects of Terfenol-D strain used in compressing the prestress mechanism. The mass term corrects for that the base mass is not infinitely large compared to the moving mass.

Returning to electroacoustics for modeling, an "effective" magnetomechanical coupling, k_{eff}, quantifying coupling for conversion of magnetic to elastic energies for the transducer can be calculated from electrical resonance and anti-resonance frequencies, f_r and f_{ar}. These frequencies are determined from the measured complex electrical impedance and admittance frequency response functions.[6] The squared effective magnetomechanical coupling factor, k_{eff}^2, is given by:

$$k_{eff}^2 = 1-\left(\frac{f_r}{f_{ar}}\right)^2 \tag{5}$$

The "dynamic method" (as opposed to the "three parameter method") is used to estimate the magnetomechanical coupling of the Terfenol-D rod in the transducer from the transducer effective magnetomechanical coupling, transducer and rod stiffnesses, and a flux leakage term, k_M^2. Based on finite element modeling of reference 7, flux leakage associated with the pick-up coil is approximated using a value of k_M^2= 0.9409. From these, the magnetomechanical coupling factor is given by:

$$k^2 = \frac{k_{eff}^2\left(k_m^H\ k_{mps}\right)}{k_M^2\left(k_m^H + \frac{k_{eff}^2\ k_{mps}}{k_M^2}\right)} \tag{6}$$

The permeability at constant stress, μ^σ, is calculated at low frequencies (i.e. at frequencies well below resonance) from the three parameter method[2]:

$$\mu^{\sigma} = \frac{q^2 E_y^H}{k^2} \tag{7}$$

Two additional material properties of potential interest to designers of Terfenol-D transducers are permeability at constant strain, μ^{ε}, and Young's modulus at constant magnetic induction, E_y^B. These properties apply to the material when it is in a blocked state, that it is when the material is prevented from straining; no rotation of magnetic domains is allowed, and would be used in modeling of, for instance a blocked electrical impedance function. From low signal linear transduction models,[2,8] one can show for Young's modulus at constant induction:

$$E_y^B = \frac{E_y^H}{1 - k^2} \tag{8}$$

and similarly, for permeability at constant strain:

$$\mu^{\varepsilon} = \mu^{\sigma}\left(1 - k^2\right) \tag{9}$$

4. RESULTS

4.1 Data analysis

Frequency response function files were analyzed with a program written using MATLAB® software to calculate Terfenol-D material properties from the 8 equations described in the previous section. The program fits circles to Nyquist electric impedance and admittance mobility loops near resonance for identification of resonant frequencies used in equations (2) and (5). The program also converts the acceleration per current data to displacement per current and averaged over low frequencies as needed for use in equation (4). Data files of the calculated material properties were imported into both a statistical analysis software program (SAS) and a graphics presentation package for analysis. The SAS reduction of these 70 files, however, indicates that the data base at this time is insufficient for a substantive evaluation of the influence of the rods, the transducers and the testers as significant experimental factors. Applied magnetic field level was the only factor identified by SAS as an experimental factor clearly influencing changes in material properties. Work is in progress on identifying appropriate functional curve fits of the data to quantify material property dependence on applied field with reliable confidence intervals. Thus, skirting the issue of statistical significance at this time, the data collected will be presented as such: material property data from the described measurements and models.

4.2 Material Property Data

Young's modulus at constant applied field versus applied field will be examined first to illustrate general trends relating to the experimental approach being used to measure material properties. Figure 3 shows the Young's modulus at constant applied magnetic field versus applied magnetic field, from the fifty test matrix for testing all rods at each drive level once. The distribution of data points suggests the existence of a decreasing trend in modulus with increasing drive level. Figures 4(a-d) break out the Young's modulus data by transducer, illustrating the concern that insufficient data are available for statistical evaluation of the influence of transducers, although "similar" trends are present in the four plots. Figures 5(a,b) shows replication results for Young's modulus at constant applied field from ten tests of rods 1 and 5 (per Table 3). Data from both of these tests do fall within the spread of data in Figure 3.

Additional material properties from the fifty test matrix shown in Figures 6-9, respectively, are magnetomechanical coupling k, axial strain coefficient, q, permeability at constant stress, μ^{σ}, and Young's modulus at constant magnetic induction, E_y^B. Magnetomechanical coupling, axial strain coefficient and permeability at constant stress from the replication results are shown in Figure 10. All reported material property values are well within the range of published values available for comparison from the literature.

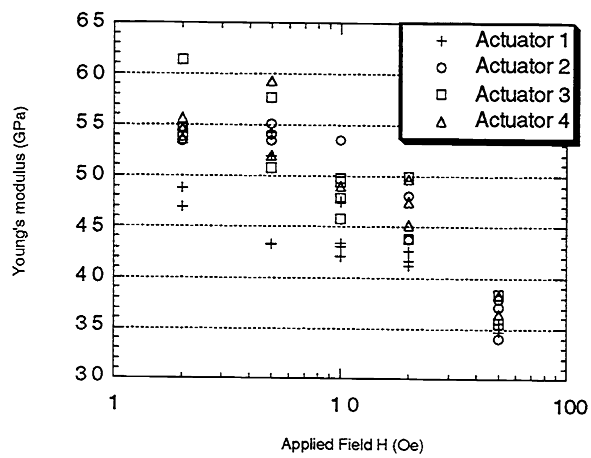


Figure 3. Young's modulus at constant applied magnetic field, E_y^H, from tests of each rod at each drive level once. 1/4" × 2" rods, 1.0 ksi initial mechanical prestress, and nominal magnetic bias of 315 Oe.

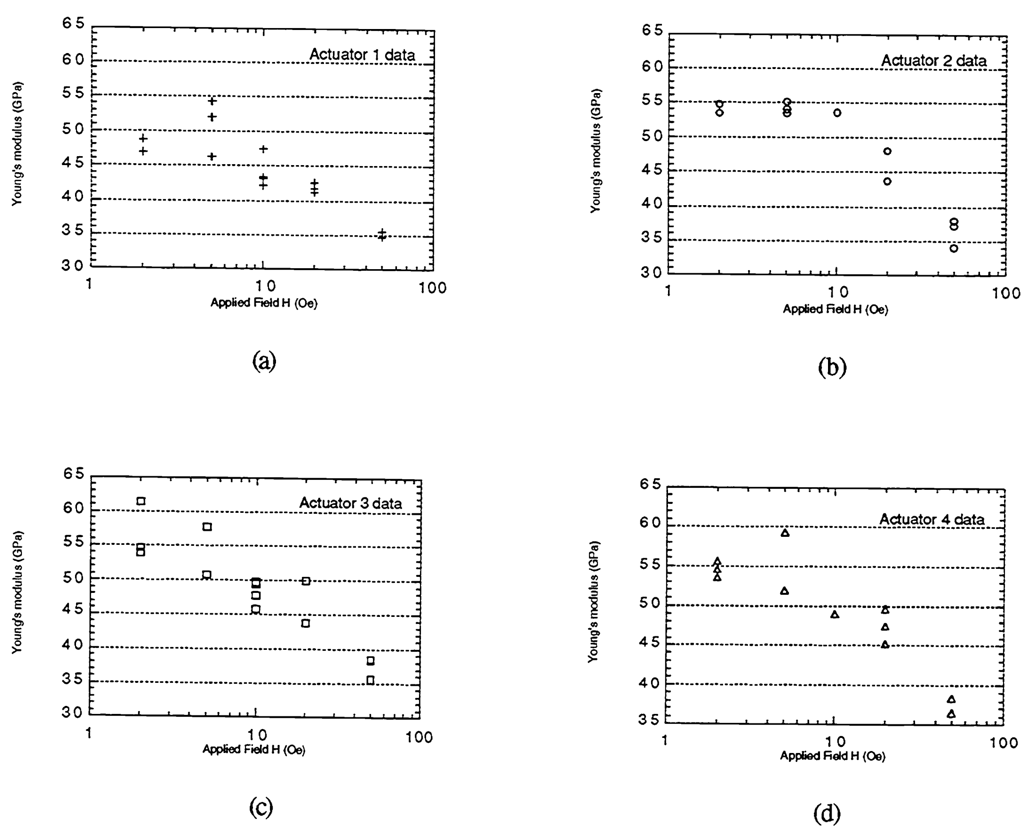
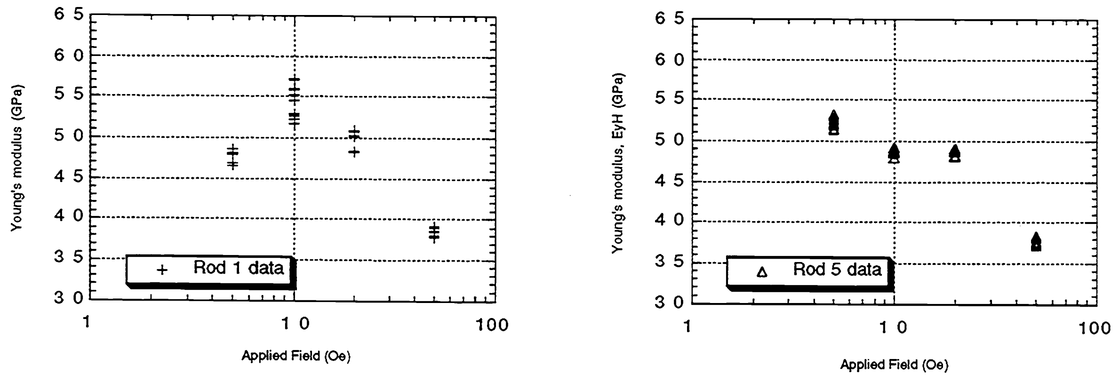


Figure 4(a-d). Young's modulus at constant applied magnetic field, E_y^H, for transducers 1-4, respectively vs. applied AC magnetic field. 1/4" × 2" rods, 1.0 ksi initial mechanical prestress, and nominal magnetic bias of 315 Oe.



(a) (b)

Figure 5(a,b). Replication tests for rods 1 (a) and 5 (b). Young's modulus at constant applied field, E_y^H, vs. applied AC magnetic field. 1/4" × 2" rods, 1.0 ksi initial mechanical prestress, and nominal magnetic bias of 315 Oe.

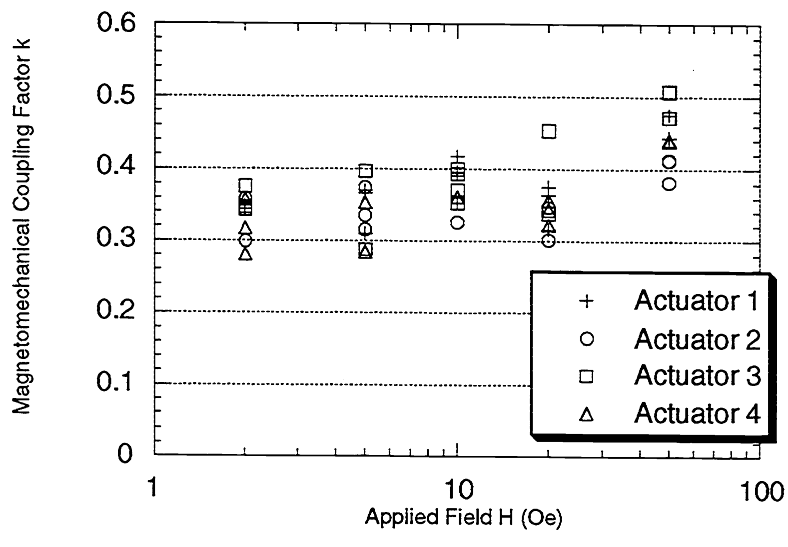


Figure 6. Magnetomechanical coupling factor, k, for all four transducers. 1/4" × 2" rods, 1.0 ksi initial mechanical prestress, and nominal magnetic bias of 315 Oe.

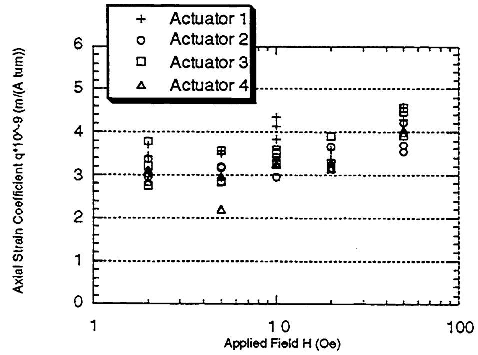


Figure 7. Axial strain coefficient, q, for all transducers. 1/4" × 2" rods, 1.0 ksi initial mechanical prestress, and nominal magnetic bias of 315 Oe.

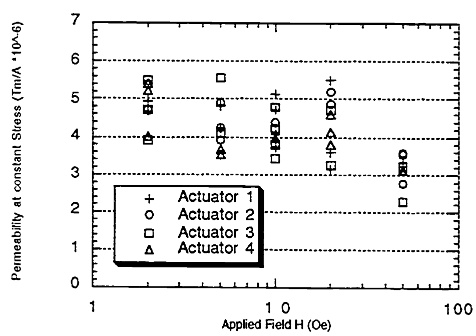


Figure 8. Permeability at constant stress, μ^{σ}, for all transducers. 1/4" × 2" rods, 1.0 ksi initial mechanical prestress, and nominal magnetic bias of 315 Oe.

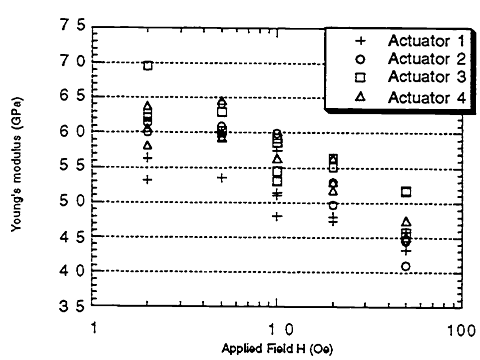
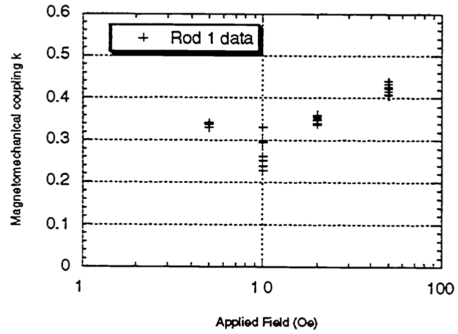
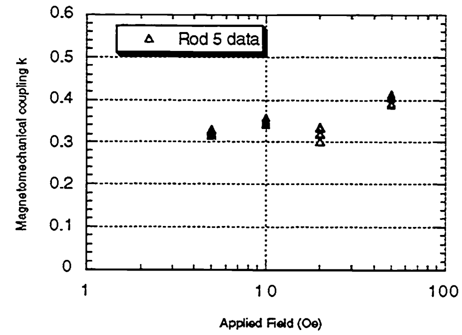


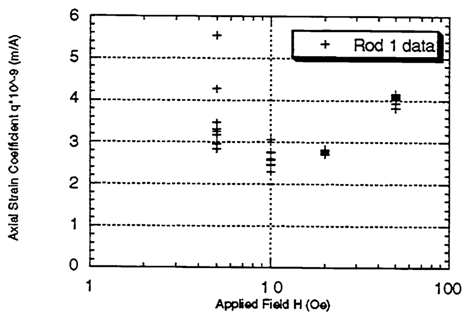
Figure 9. Young's modulus at constant induction, E_y^B, for all four transducers. 1/4" × 2" rods, 1.0 ksi initial mechanical prestress, and nominal magnetic bias of 315 Oe.



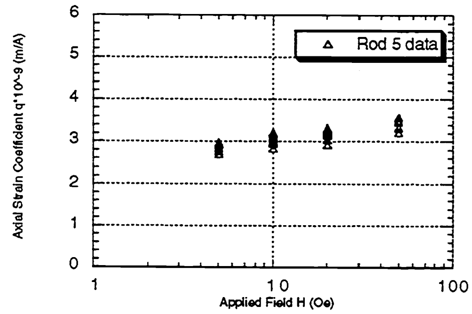
(a)



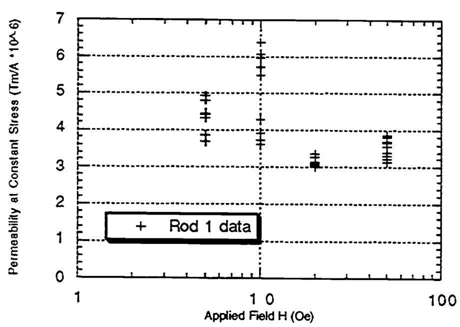
(d)



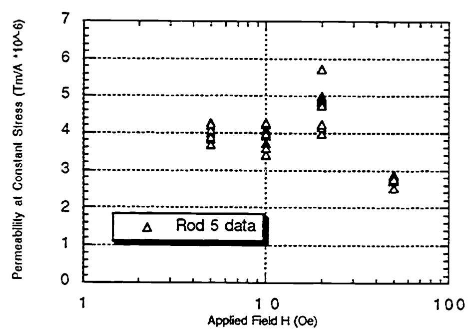
(b)



(e)



(c)



(f)

Figure 10. Comparison of replication results of magnetomechanical coupling factor, k, axial strain coefficient, q, and permeability at constant stress for rods number 1 (a, b, c) and 5 (d, e, f), respectively.

5. CONCLUSIONS

An experimental approach for conducting measurements under magnetic bias and mechanical prestress conditions typical of transducer applications for Terfenol-D was presented. Some of the benefits of being able to characterize Terfenol-D material properties in transducers were discussed. A summary was given of equations available from electroacoustic, mechanical and transduction models for using measured transducer complex impedance functions and acceleration per unit current frequency response functions to obtain material property data. Preliminary data on the behavior of ten samples of Terfenol-D under varied applied AC magnetic fields was presented, together with repeatability data for two samples chosen from the set.

6. ACKNOWLEDGMENTS

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