Terfenol-D elasto-magnetic properties under varied operating conditions using hysteresis loop analysis

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ABSTRACT

This paper presents an experimental study of the effects of varied magnetic bias, AC magnetic field amplitude and frequency on the characteristics of hysteresis loops produced in a magnetostrictive transducer. The study uses a magnetostrictive transducer designed at Iowa State University that utilizes an 11.5 cm (4.54 in) long by 1.27 cm (0.5 in.) diameter cylindrical Terfenol-D rod. This transducer allows controlled variation of the following operating conditions: mechanical prestress, magnitude and frequency of AC magnetic field, and magnetic bias. By performing extensive experimental tests, material property trends can be developed for use in the optimization of transducer design parameters for different applications. For the results presented, the magnetic bias, the AC magnetic field amplitude, and the frequency of excitation were independently varied while temperature, mass load and prestress were kept constant. The minor hysteresis loops of the strain versus applied magnetic field, flux density versus applied magnetic field, and magnetization versus applied magnetic field are presented and compared. Material property trends identified from the minor loops are presented for the axial strain coefficient, permeability, susceptibility, and energy losses.

Keywords: Terfenol-D, magnetostrictive transducers, hysteresis loops

1. INTRODUCTION AND BACKGROUND

Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_{1.9}$) is a highly magnetostrictive material developed in the 1950's at the Naval Ordinance Labs (now called NSWC). It is an alloy of Terbium, Iron, and Dysprosium that can achieve strains on the order of 1000x10^-6 m/m when exposed to a magnetic field under certain conditions. This material is the active element in many magnetostrictive transducers that are being developed, tested, and manufactured at the present.

One of the obstacles that was found in the design of these magnetostrictive transducers is that the behavior of the Terfenol-D rod is highly dependent on the external conditions under which the transducer operates as well as on the transducer design itself. Work detailed in [3] used swept sine measurements to identify trends in the elasto-magnetic properties of a transducer developed at Iowa State University based on variations in the following applied conditions: mechanical prestress, magnitude and frequency of AC magnetic field, and magnetic bias. Just as the mechanical behavior of Terfenol-D varies greatly with external conditions so does its hysteretic behavior.

A study of the hysteresis in a material is useful in determining several material properties as well as in gaining a more in depth understanding of the physical behavior of the material as is discussed in [2]. It is useful to examine two varieties of hysteresis loops. First are the major loops generated with large symmetric applied fields. Second are the minor loops that are created when the field is reversed twice before reaching its maximum value. There is a change in shape of the minor loops depending on the magnitude of the applied field at the reversal point as well as other factors. This indicates that the material properties determined from these curves also change. It is thus necessary to study the variation in the minor hysteresis loops as various external conditions are changed so as to properly understand material behavior when subject to a variety of interacting operating conditions. Through this study it is possible to identify some trends that will make it possible to optimize the transducer behavior for specific operations.

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2. TESTING PROCEDURE

2.1 Equipment

The objectives of the tests dictate that the transducer used allow for precise control and regulation of operating conditions. The study uses a magnetostrictive transducer developed by Iowa State University (ISU), discussed in [4] and shown in Figure 1. By attaching the drive coil to a variable current source it is possible to vary the frequency and magnitude of the current through the solenoid, thus varying the frequency and magnitude of the magnetic field applied to the Terfenol-D rod. In addition, the prestress bolt at the base and the Belleville spring washer in the head allow for the Terfenol-D to be placed under a variable mechanical prestress. The cylindrical permanent magnet surrounding the coil is slit to reduce eddy current losses. Its magnetization determines the range of magnetic biases which can be set up by running a DC current through the coil. Finally, various mass loads can be attached to the top of the head.

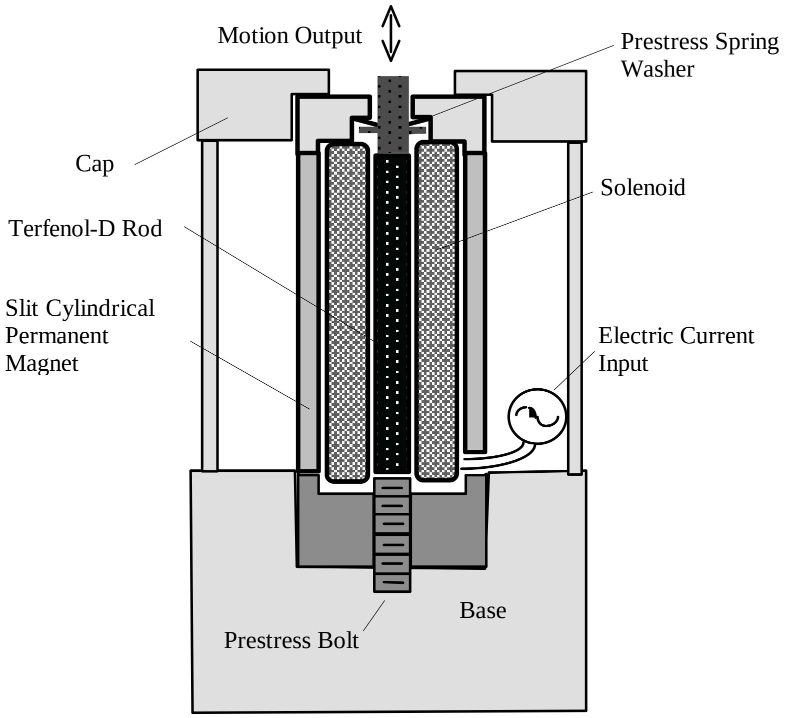

Figure 1: Schematic of Terfenol-D magnetostrictive transducer designed at ISU

The accuracy of the results of the tests that were performed is highly dependent on the accuracy of the method of measuring and calculating the strain of the Terfenol-D in the transducer. Two methods were available for this purpose: measurement of the displacement of the head or measurement of the acceleration of the head. It was determined through numerous tests that both methods needed to be used. At frequencies below 10 Hz, the magnitude of the acceleration of the head was too small for the available accelerometers to measure accurately. Thus it was necessary to use the Linear Variable Differential Transducer (LVDT), a displacement sensor based on changing reluctance. At higher frequencies (above 10Hz) the data from the LVDT was found to be inaccurate, however, an accelerometer could be used. The data received by this method had to be converted to displacement and then to strain by a double integration method. Both methods of data collection and analysis was used for these tests.

Additional equipment used in these tests include a Techron 7780 amplifier in current control mode as the current source for the drive coil, a Tektronix 2642A Personal Fourier Analyzer which produced the reference signal and collected data, and thermo-couples located near the ends of the Terfenol-D rod which monitored the temperature of the tests.

2.2 Testing Matrix

The three experimental factors that were studied were magnitude and frequency of AC magnetic field and magnitude of DC magnetic bias. Four frequencies, five AC magnetic field magnitudes, and five magnetic bias values were varied for these tests, yielding a four by five by five matrix for a total of 100 tests. Additional experimental factors such as temperature and mechanical prestress were held constant during all tests.

Tests were run at frequencies of 1 Hz, 100 Hz, 500 Hz, and 1.25 kHz. 1 Hz was picked because it represents a quasi-static state and 1.25 kHz was picked because it is near the first axial resonant frequency of the transducer. In addition to this variation in frequency, the magnitude of the AC magnetic field was also changed between tests. The following five magnitudes were chosen because they have been used as standard operating conditions in previous tests: (0 to peak) 25(3000), 50(4000), 100(8000), 150(12000), and 200(16000) Oe(A/m). Finally, five levels of magnetic bias were also picked which represent five starting points on the major hysteresis curve. The five levels that were decided upon were 100(8000), 200(16000), 300(24000), 400(32000), and 500(40000) Oe(A/m). Figure 2 shows how minor hysteresis loops relate to the major loop for a 1Hz test at a 5kA/m drive level.

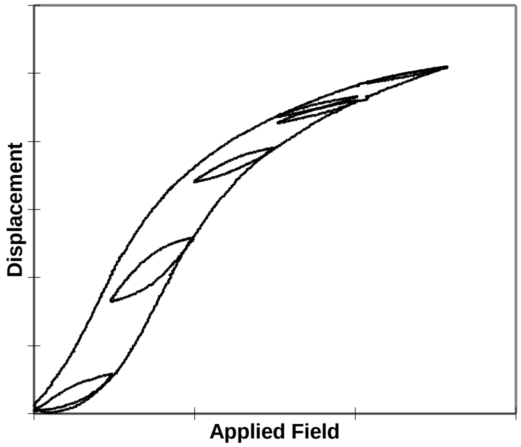

Figure 2: Quasi-static major and minor Displacement vs. Applied Field hysteresis loops. Minor loops have amplitude 5 kA/m AC and biases of 5, 15, 25, 35, and 45 kA/m

Ten tests would have given information that is of no interest since the magnetic bias is larger than the amplitude of the applied field which causes frequency doubling. These tests were not run and are blank in the presentation of the results.

The remaining external conditions that have been shown, through previous work (see [3]), to have an effect on the behavior of the transducer are mechanical prestress, mass load, and temperature. For this project the mechanical prestress was set at 1ksi (6.9GPa) and the mass load used was 500 grams. These settings are consistent with those of previous tests, making a comparison possible for verification of observed parameter magnitudes. Holding the temperature constant proved to be more difficult since the tests run, while short, generated a large amount of heat. The temperature was monitored using thermocouples, and most tests showed a variation of under 10°C above room temperature.

2.3 Data Analysis

Three of the channels of collected data were calibrated voltages proportional to the voltage input to the transducer, current input to the transducer, and voltage output from the monitoring coil. A fourth channel was used to measure output from either the LVDT or the accelerometer. All four channels were recorded by the Tektronix 2642 Personal Fourier Analyzer. This data was converted to magnetization (M), magnetic flux density (B), applied field (H), and strain yielding hysteresis loops. The most interesting results of these plots will be discussed in the following sections. Also calculated were the following characteristics of the graphs: average slope, instantaneous slope, and area within the hysteresis loop. These calculations yield information about the properties susceptibility (χ), permeability (μ), and axial strain coefficient (d33) as well as energy losses in the system.

3. RESULTS

3.1 Data grouped by frequency: Strain vs. H

Of the calculated results the most intuitive and useful are the graphs of strain versus applied field (H). Two of these are shown in Figures 3 and 4. They show data from the 1 Hz (quasi-static) and 1.25 kHz (resonance) tests respectively.

In Figure 3 the horizontal rows show the results from tests of the same applied field magnitude while the vertical columns show the results of tests with the same magnetic bias. As is to be expected, each column shows the trend that as the magnitude of the applied field increases so does the strain output of the Terfenol-D. It is also evident from Figure 3 that there is a magnetic bias of about 200 Oe which gives the largest strain output for a given applied field. This bias, however, also shows evidence of large energy losses for a given applied field, as seen in the hysteresis shown by the area enclosed in the minor loops. Less hysteresis is found at the higher magnetic biases as the minor loop is pushed closer to the saturation region of the major hysteresis loop. However, these biases also give less strain output. Loss and maximum strain information corresponding to Figure 3 are shown in Table 1. Figure 3 shows results from the 1 Hz tests, and the majority of trends discussed here also hold for the 100 Hz and 500 Hz results. However, different results are found for the tests run near resonance (1.25 kHz) which are shown in Figure 4.

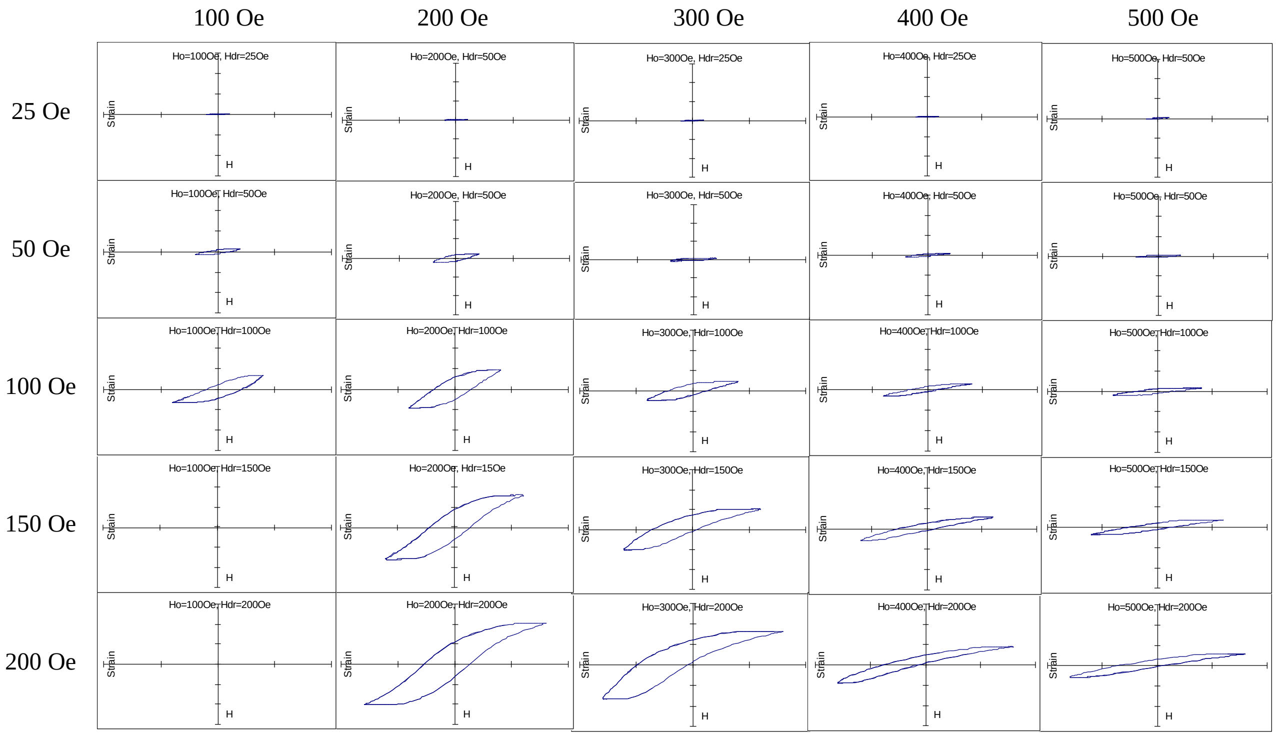

Figure 3: Strain vs. H 1Hz test results, Strain: -0.0006ppm->0.0006ppm, H: -20,000A/m->20,000A/m

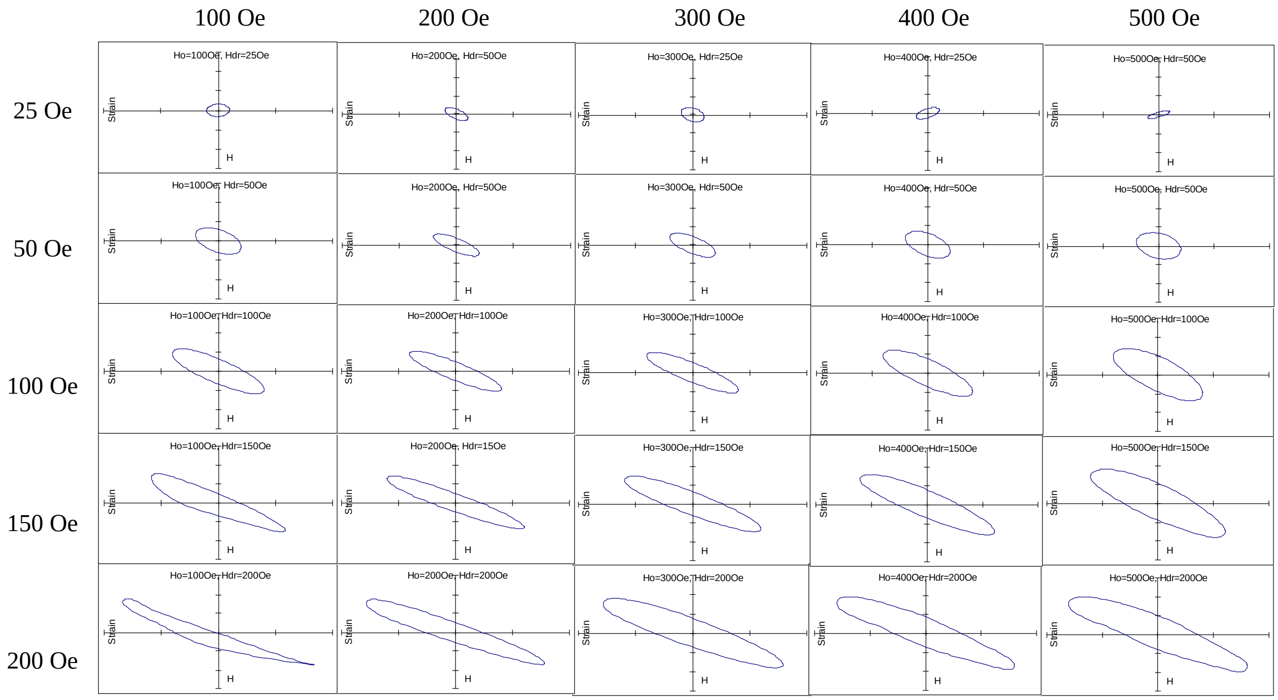

Figure 4: Strain vs. H, 1.25kHz test results, Strain: -0.0006ppm->0.0006ppm, H: -20,000A/m->20,000A/m

Ho	200 Oe		300 Oe		400 Oe		500 Oe	
Hdr	ε_{max} µm/m	Area ε•Oe	ε_{max} µm/m	Area ε•Oe	ε_{max} µm/m	Area ε•Oe	ε_{max} µm/m	Area ε•Oe
25 Oe	1.36E-05	3.48E-02	4.18E-06	4.57E-01	6.88E-06	6.95E-01	2.52E-06	2.62E-01
50 Oe	8.78E-05	8.90E+00	3.50E-05	6.28E+00	3.52E-05	2.21E+00	1.95E-05	4.09E-02
100 Oe	3.72E-04	2.60E+02	1.82E-04	1.68E+02	1.24E-04	6.61E+01	7.40E-05	3.27E+01
150 Oe	6.38E-04	1.26E+03	4.10E-04	1.07E+03	2.30E-04	3.45E+02	1.47E-04	1.66E+02
200 Oe	8.16E-04	3.47E+03	6.62E-04	3.08E+03	3.64E-04	1.16E+03	2.32E-04	4.89E+02

Table 1: Max Strain and Loss data for H versus Strain at 1 Hz

Ho	200 Oe		300 Oe		400 Oe		500 Oe	
Hdr	ε_{max} µm/m	Area ε•Oe	ε_{max} µm/m	Area ε•Oe	ε_{max} µm/m	Area ε•Oe	ε_{max} µm/m	Area ε•Oe
25 Oe	1.40E-04	1.07E+02	1.54E-04	1.38E+02	1.21E-04	1.36E+02	7.93E-05	8.76E+01
50 Oe	2.43E-04	2.90E+02	2.62E-04	3.41E+02	2.84E-04	3.99E+02	2.84E-04	4.30E+02
100 Oe	4.18E-04	7.60E+02	4.23E-04	7.15E+02	4.90E-04	8.86E+02	5.48E-04	1.07E+03
150 Oe	5.62E-04	1.30E+03	5.88E-04	1.28E+03	6.40E-04	1.30E+03	7.16E-04	1.58E+03
200 Oe	6.94E-04	2.32E+03	7.20E-04	2.21E+03	7.70E-04	1.98E+03	7.96E-04	2.09E+03

Table 2: Max Strain and Loss data for H versus Strain at 1.25 kHz

Figure 4 shows the same general trends with respect to total strain at varied bias and drive level that were observed in the 1 Hz results. However, these results (run at just above the transducer's resonance frequency) also exhibit several differences. The most obvious of these is found in the shape of the minor hysteresis loops. Whereas in the 1 Hz results mainly sigmoid shapes are evident, the 1.25 kHz results are described by oval shaped loops. Another difference is the direction of the average slope of the hysteresis loops. As should be expected, it is found that above resonance the slopes of the minor loops switch from positive to negative. One more difference that can be observed is that there are not such drastic changes in the energy losses with bias at 1.25 kHz as there were at 1 Hz. This can been most clearly seen by a comparison of the shapes of the hysteresis loops at 200 Oe with either the 400 Oe or 500 Oe columns and can be seen numerically in the data shown in Table 2. In addition to the lack of variation in the amount of energy loss with bias, there is also a lack of change in the amount of strain that was output as the magnetic bias was changed. In fact, the magnetic bias has very little effect on the results at 1.25 kHz while it had great effect at lower frequencies.

3.2 Data grouped by Magnetic Bias: Strain vs. H

As was noted above, a magnetic bias of 200 Oe produces the most strain output for a given applied field for most, if not all, frequencies. It is therefore interesting to look at all tests run at this bias together.

Figure 5 shows strain versus applied field results like those found in Figures 3 and 4, however, here all the minor loops shown are generated at a magnetic bias 200 Oe. The horizontal rows are still tests run at the same applied field while the columns now show the results of tests run at the same frequencies. The change in direction of the slopes that occurs above resonance (discussed above) is apparent. This is examined more thoroughly in Figure 6, where minor loops at eight frequencies and a strain per applied field frequency response function (FRF) is shown. Strain amplitude and energy losses are observed to vary with frequency. Another interesting observation about Figure 5 is that while the 500 Hz and 1.25 kHz tests yield oval hysteresis loops, the 1 Hz and 100 Hz tests yield sigmoid shaped minor loops which shows that there are more energy losses per unit strain at higher frequencies. Since the shape of the curve is determined by the phase shift between the strain and applied field, this indicates a change in phase shift as the frequency of the applied field approaches the resonance frequency of the transducer. An additional interesting and useful observation is the fact that the area enclosed in the hysteresis loops varies much more with frequency than the output strain does, as shown in Table 3. This implies that using this magnetic bias an amplitude of output strain can be chosen by picking the corresponding amplitude of applied field while the amount of energy losses can by picked by choosing the frequency of applied field.

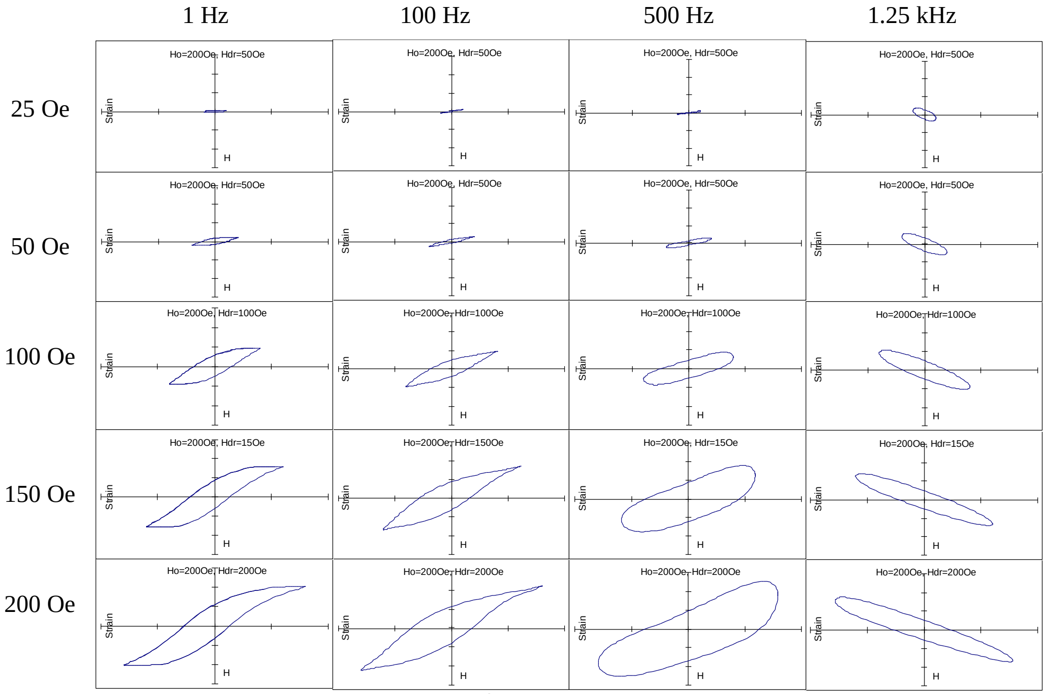

Figure 5: Strain vs. H, Magnetic Bias of 200 Oe test results, Strain: -0.0006ppm->0.0006ppm, H: -20,000A/m->20,000A/m

Freq.	1 Hz		100 Hz		500 Hz		1.25 kHz	
Hdr	ε_{max} μm/m	Area ε•Oe	ε_{max} μm/m	Area ε•Oe	ε_{max} μm/m	Area ε•Oe	ε_{max} μm/m	Area ε•Oe
25 Oe	1.36E-05	3.48E-02	3.62E-05	8.05E+01	3.53E-05	9.37E+01	1.40E-04	1.07E+02
50 Oe	8.78E-05	8.90E+00	1.14E-04	4.44E+02	1.17E-04	5.14E+02	2.43E-04	2.90E+02
100 Oe	3.72E-04	2.60E+02	3.84E-04	2.81E+03	3.48E-04	2.95E+03	4.18E-04	7.60E+02
150 Oe	6.38E-04	1.26E+03	6.76E-04	7.31E+03	7.19E-04	8.62E+03	5.62E-04	1.30E+03
200 Oe	8.16E-04	3.47E+03	8.86E-04	1.33E+04	1.01E-03	1.62E+04	6.94E-04	2.32E+03

Table 3: Max Strain and Loss data for H vs. Strain at Ho = 200 Oe

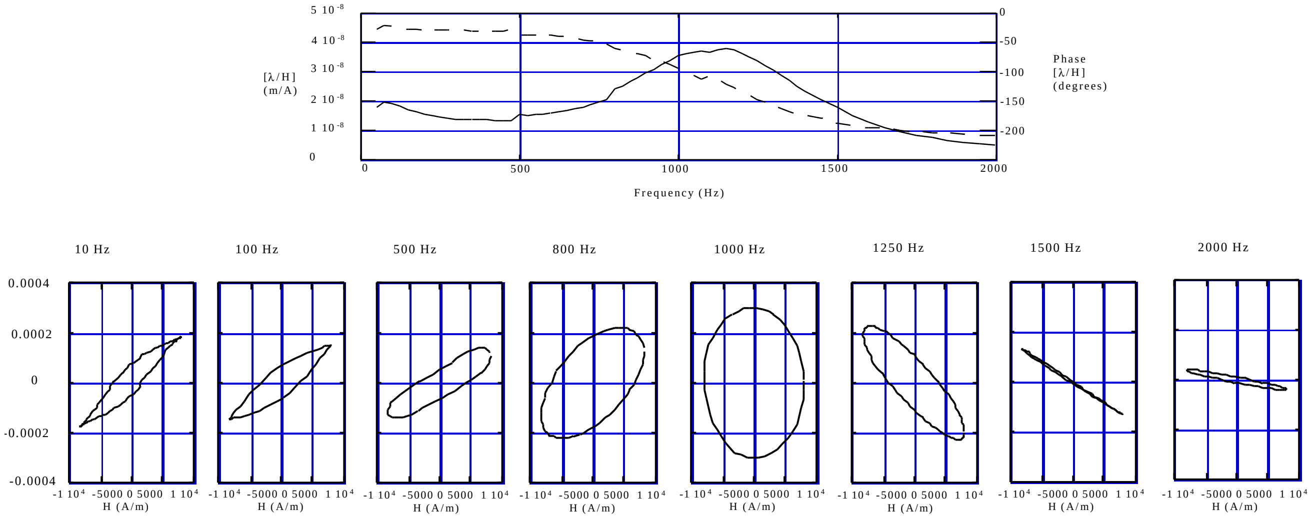

Figure 6: (top) FRF strain versus applied field magnitude and phase. (bottom) strain versus applied field minor loops for 200 Oe magnetic bias.

3.3 Strain vs. H compared to Strain vs. M : 1 Hz

The previous sections dealt solely with strain versus H hysteresis curves which reflect the behavior of the transducer as a system. It is also interesting to look at strain versus magnetization (M) curves which reflect the Terfenol-D rod performance. The strain versus M results for the 1 Hz tests are shown in Figure 7.

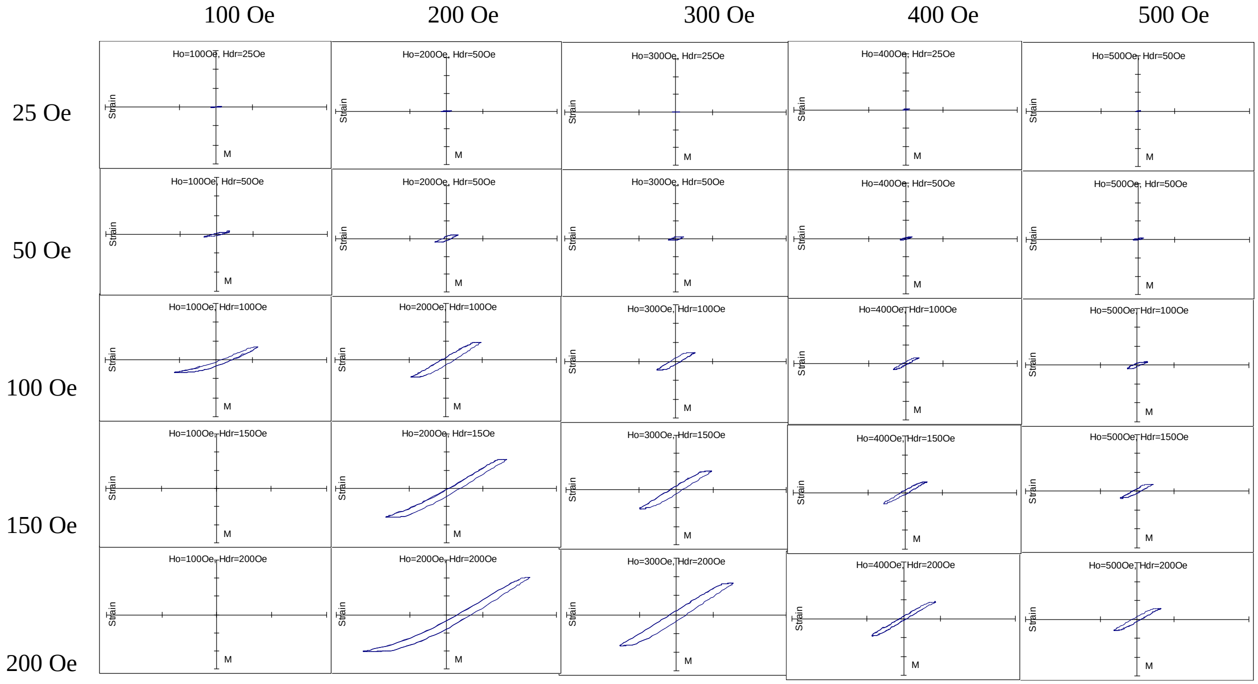

Figure 7: Strain versus Magnetization, 1 Hz test results, Strain: -0.0006 ppm->0.0006 ppm, M: -300000 A/m->300000 A/m

As in Figures 3 and 4, the rows in Figure 7 show results of tests with the same applied field magnitude while the columns show the results of tests with the same magnetic bias. These results are similar in shape and size to those seen when strain is plotted against magnetic flux density B. This is a result of the small magnitude of H with respect to B in the equation $B = \mu_o(H+M)$ which was used to calculate M. The most obvious characteristics of the plots in Figure 7 are the comparative lack of hysteresis and the quasi-linear nature of the minor loops. Thus, it is apparent that it would be preferred to control the transducer based on magnetization (or equivalently magnetic flux density) rather than applied field. Once again the 200 Oe magnetic bias tests show the largest strain outputs per input field level but also involve the most energy losses due to hysteresis as is evident from Table 4. In fact, most trends are similar for the strain versus magnetization and the strain versus applied field results. The one exception to this is that while applied field remained constant, magnetization decreased with increasing magnetic bias.

Ho	200 Oe		300 Oe		400 Oe		500 Oe	
Hdr	ε_{max} µm/m	Area ε•Oe	ε_{max} µm/m	Area ε•Oe	ε_{max} µm/m	Area ε•Oe	ε_{max} µm/m	Area ε•Oe
25 Oe	1.36E-05	0.00267	4.18E.06	0.002292	6.88E-06	0.001902	2.52E-06	0.000833
50 Oe	8.78E.05	0.004211	3.50E-05	0.007921	3.52E-05	0.000302	1.95E-05	0.010071
100 Oe	3.72E.04	0.189946	1.82E-04	0.304244	1.24E-04	0.140373	7.40E-05	0.067676
150 Oe	6.38E-04	0.747256	4.10E-04	1.984342	2.30E-04	0.683338	1.47E-04	0.328681
200 Oe	8.16E-04	1.585666	6.62E-04	5.208737	3.64E-04	2.332707	2.32E-04	1.016957

Table 4: Max Strain and Loss data for Strain vs. M at 1 Hz

4. MATERIAL PROPERTIES

The above section presents trends which can aid in the choice of external conditions to achieve a specific purpose. The results presented also give information about the material properties of the Terfenol-D - transducer system. For example, axial strain coefficient (d_{33}), permeability (μ), and susceptibility (χ) are defined as the slopes of the strain versus applied field magnitude, magnetic flux density versus applied field magnitude, and magnetization versus applied field magnitude curves respectively. Values for these material properties were calculated and plotted versus the external conditions that were changed. This data is presented in Figures 8, 9, and 10.

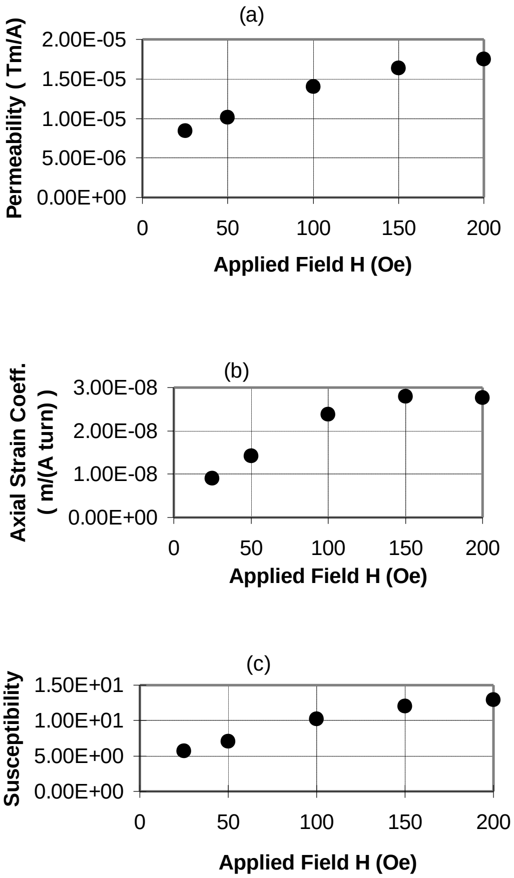

Figure 8 : (a) Permeability, (b) Axial Strain Coefficient, (c) Susceptibility vs. Applied field for frequency = 100 Hz, Magnetic bias = 200 Oe

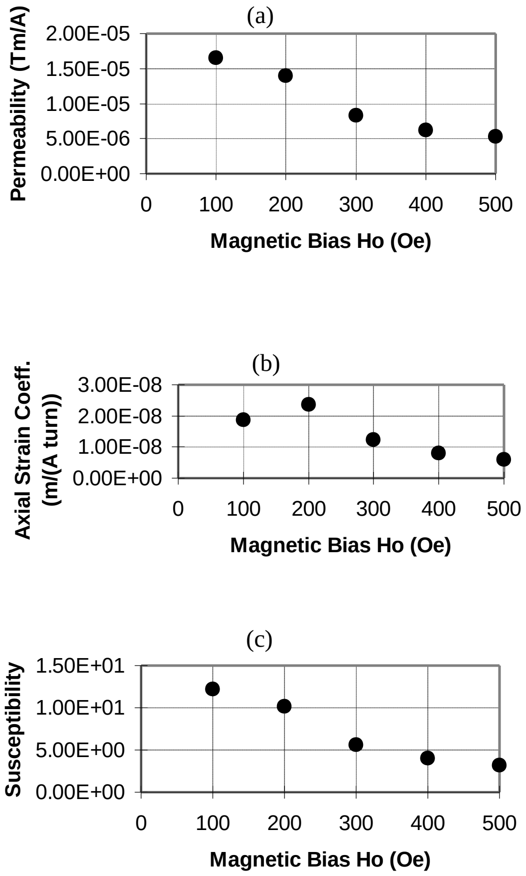

Figure 9 : (a) Permeability, (b) Axial Strain Coefficient, (c) Susceptibility vs. Magnetic Bias for freq = 100 Hz, Applied Field = 100 Oe

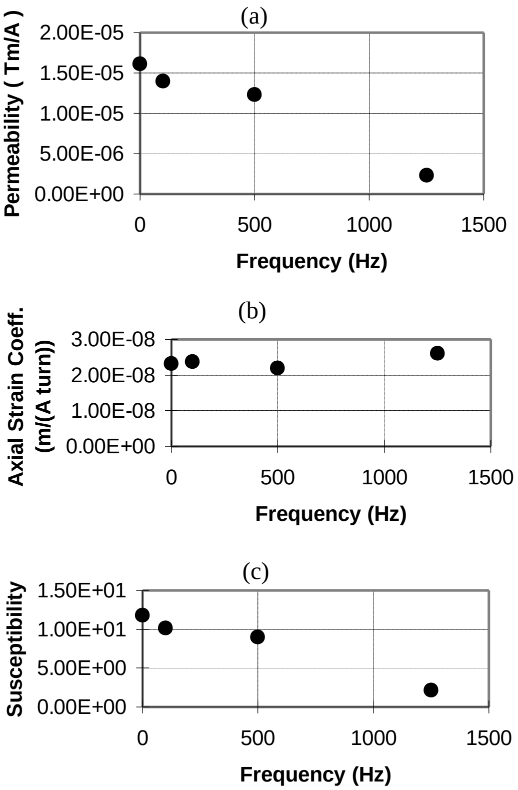

Figure 10 : (a) Permeability, (b) Axial Strain Coefficient, (c) Susceptibility vs. Frequency for Applied Field = 100 Oe, Magnetic Bias = 200 Oe

The figures show definite trends as operating conditions are changed. For instance, there is a distinct increasing trend in all three properties as applied field is increased (Figure 8) and a decreasing trend as magnetic bias is increased (Figure 9). As frequency is increased, both permeability and susceptibility show decreasing trends while the axial strain coefficient maintains a constant value. It is interesting to note that the trends for permeability and susceptibility are identical. This is a result of the close relation between magnetization and magnetic flux density as discussed earlier. All of these results have special relevance to work done in modeling Terfenol-D magnetostrictive transducers. In previous models the permeability and other material properties were used as constant values. It can be seen from these graphs, however, that these material properties are not constants but are in fact complicated functions of applied field magnitude and frequency, magnetic bias. This agrees with [7] where sensitivity to mass load, mechanical prestress, and temperature are also indicated.

Figures 8, 9, and 10 show that the average material property μ, χ and d33 are not constants but rather change with external conditions. Furthermore, since these properties are defined as the slopes of graphs that exhibit hysteretic behavior they will vary with the point on the minor loop at which they are measured. The average material property data is generated by calculating the nominal slope of the minor loops in question. This was done by determining the slope of the line joining the tips of the appropriate loop. The instantaneous slopes at each point along the loop were also calculated. Figure 11 shows both instantaneous and average permeability data. The instantaneous slope is the solid line with the spikes at 0, 65, and 130 representing the turn-around points in the minor loop and the average slope is the bold line for the test run with an applied field magnitude of 100 Oe, and a frequency of 100 Hz, and a magnetic bias of 200 Oe. It is noteworthy that there is a significant difference between the average and instantaneous slopes. In fact, it was found that for 91.4 % of the points on the loop the difference between the instantaneous slope and the average is greater than 10%. This implies that using the average slope of the minor hysteresis loop as the value for the material property that corresponds to that loop will not give an accurate result for some applications.

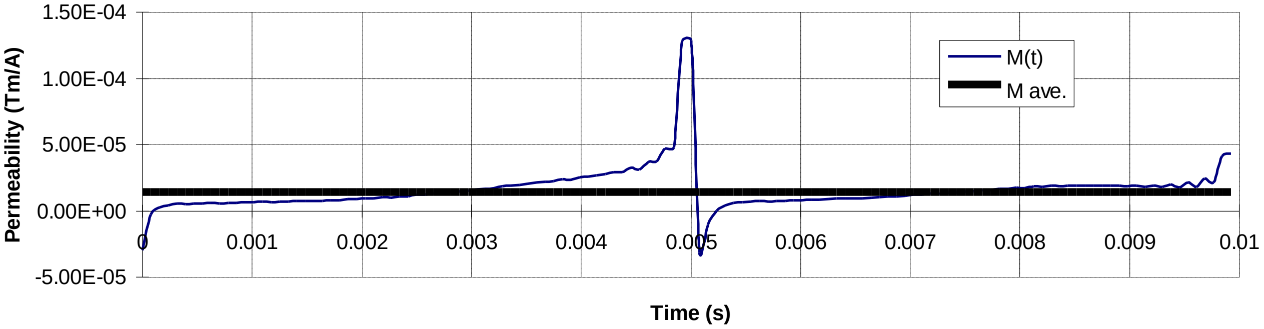

Figure 11: Average and Instantaneous Permeability data for test run at applied field of 100 Oe, frequency of 100 Hz and magnetic bias of 20 Oe. Solid line = instantaneous, bold line = average.

5. CONCLUSIONS

An experimental study of the effects of magnetic bias, frequency and AC magnetic field amplitude on the minor hysteresis loops generated by a Terfenol-D magnetostrictive transducer was presented. The procedure used to run the tests was outlined and the results were discussed. A comparison was made between hysteresis loops from strain versus applied field data for 1 Hz and 1.25 kHz tests. The observation was made that despite many differences, both sets of results showed that a magnetic bias of 200 Oe gave the preferred output. A study of all tests run at this magnetic bias showed that there was a distinct change in shape of the hysteresis loop as frequency was increased. A set of strain versus magnetization hysteresis loops were compared to the strain versus applied field hysteresis loops and the fact that control based on magnetization would give more linear results was noted. The material properties, permeability, susceptibility, and axial strain coefficient, which were calculated from the hysteresis loops were discussed. Finally, a comparison of the average and instantaneous slopes of a hysteresis loop was presented in which it was pointed out that use of the average slope as a constant is inaccurate.

6. ACKNOWLEDGMENTS

This work was conducted in the Department of Aerospace Engineering and Engineering Mechanics in the College of Engineering at Iowa State University. The research was largely made possible through the support of NSF Young Investigator award CMS-9457288. The research of L.E. Faidley and B.J. Lund was supported by an NSF Research Experience for Undergraduates supplemental award to grant CMS-9457288, and the research of F.T. Calkins was supported by NASA Graduate Student Research Program fellowship award #51254, Dr. Richard Silcox program manager. The authors also express thanks for the technical knowledge of Marcelo Dapino.

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