Effect of prestress on the dynamic performance of a Terfenol-D transducer

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ABSTRACT

The performance of magnetostrictive Terfenol-D is highly dependent on the state of the material and in particular on the mechanical prestress. This paper presents an experimental investigation of the effect of prestress on the dynamic performance of a Terfenol-D transducer. The effects of both prestress and magnetic bias on the near DC transducer performance are also presented. Experimental results demonstrate the sensitivity of the transducer performance in terms of strain, strain rate with applied field, and material properties to relatively small changes in initial mechanical prestress. Trends in material properties, Young's Modulus, magnetomechanical coupling factor, permeability, dynamic strain coefficient, and mechanical quality factor with prestress and drive level are developed. In addition, the effect of magnetic bias and frequency of operation on the strain at different applied fields are examined and shown to significantly influence transducer output at a given prestress level. For the transducer as operated in this study, including the appropriate magnetic bias, both the magnetomechancial coupling and the strain coefficient are optimized with a prestress of 1.0 to 1.25 ksi.
Keywords: Terfenol-D, magnetostriction, magnetostrictive transducer, magnetomechanical effect

2. MOTIVATION

Mechanical prestress is considered one of the primary factors, along with magnetic field and temperature, which influences a magnetostrictive material's performance[1]. Therefore, it is of interest to the Terfenol-D designer to thoroughly investigate the effects of prestress on the performance of a Terfenol-D transducer. This will aid in the development of accurate models of transducer designs and assist in specification of a prestress optimized for a given application. In an effort to help define the investigation presented here, we pose two questions. First, what is the impact of prestress on the dynamic performance of a prototype Terfenol-D transducer? And second, will this information allow us to optimize transducer properties and performance?

3. THE EFFECT OF PRESTRESS

A compressive mechanical load or prestress on a Terfenol-D sample has several observable effects. First, the total strain capability of the material is increased by more than the initial compressive strain. Second, the ability of the material to survive high accelerations and shock conditions improves since Terfenol-D is very brittle in tension (tensile strength ~28 MPa) versus compression (compressive strength ~700 MPa)[7]. And finally, the Terfenol-D performance, as measured by the material properties, can be greatly improved or degraded.

This first effect is often illustrated by the changing slope and maximum strain in the double sided strain versus applied magnetic field plots (butterflies), obtained under quasi-static conditions[7]. The butterflies increase in slope and saturation strain with increasing prestress until a peak is reached. Further increases in prestress result in a decrease in the slope and much larger applied fields required to reach saturation strain.

The effect of prestress on performance is of particular interest to the design engineer, as it will allow one to optimize the transducer performance. Research into the effect of prestress on magnetostriction shows many subtle effects, such as interaction with magnetic bias. Moffet et al. provide one of the most thorough experimental investigations of the effect of prestress on Terfenol-D material properties[2]. They show the effect of drive level (100 to 2000 Oe 0-pk) and prestress (1.0 to 9.0 ksi), with an optimized magnetic bias, on the material properties. They conclude that "the results of d_{33} [axial strain coefficient, q], μ^T_{33} [permeability], and s^H_{33} [mechanical compliance] are dependent on stress and the magnetic field, so proper mechanical prestress and magnetic bias conditions are critical to successful use of Terfenol-D in transducers and actuators."

Numerous studies have noted that different prestress and magnetic bias conditions can result in clear trends, including maxima or minima in axial strain coefficient (strain rate with applied field), magnetomechanical coupling, permeability, and peak mechanical output[2-5]. Some studies indicate that it is not possible to optimize all parameters with prestress simultaneously. Schulze et al. found the optimal prestress for coupling and strain coefficient to be 0.29 and 1.12 ksi respectively[3]. They noted a sharp change in coupling with prestress around the optimum prestress. Greenough et al. identified a minimum in permeability with prestress at 0.29 ksi[4]. Neither study reports the interaction with magnetic bias or drive level. In addition, preliminary studies by the authors found a maximum transducer acceleration output at ~1.9 ksi[6] for a broadband, low field drive. Other trends have been reported, such as an increase in Young's Modulus with prestress[2]. The authors have noted trends in the electrical impedance function and material properties changing at different prestress[8]. It is important to note that it is not always possible to compare results from different studies because other operating conditions such as load, temperature, and the prestress mechanism, which have a significant effect on performance, are different.

While the results found in literature provide an excellent background, many studies concentrated on quasi-static measurements made in laboratory setups. Models describing the relation of quasi-static results to dynamic transducer operation have not been developed, nor has the practical usefulness of prestress optimization for dynamic performance criteria been addressed. Thus the current study attempts to paint a more complete picture of the effect of prestress on a transducer performance by considering the interaction of prestress with magnetic bias and drive level under quasi-static conditions (sections 5 to 7) and under dynamic operating conditions (sections 8 to 10).

4. EXPERIMENTAL SCOPE

Investigation into the dynamic effect of prestress at various drive levels is accomplished with several sets of tests. First, the effect of prestress from 0.5 (3.49)to 1.5 (10.34) ksi (MPa) (without a magnetic bias) on high drive level quasi-static output is investigated in section 5. Second, the magnetic bias is varied for a given prestress to show the effect of magnetic bias on quasi-static operation in section 6 and 7. The effect of prestress with an optimized magnetic bias on strain output is presented. Third, a comparison is made between strain vs. applied field results under quasi-static (0.7 Hz) and dynamic (400 Hz) conditions in section 8. Fourth, input electrical impedance functions, the basis for transducer performance characterization using electroacoustic theory, are compared at different bias conditions and dynamic operating conditions in section 9. Finally, material properties are calculated using impedance analysis and a linear transduction model in section 10. Four prestress levels, 0.75 (5.17), 1.0 (6.89), 1.25 (8.62), and 1.5 (10.34) ksi (MPa), each with a different "optimized" magnetic bias were investigated at four drive levels, AC applied magnetic field amplitudes (0 to peak) of 25 (2000), 50 (4000), 75 (6000), 100 (8000) Oe (A/m).

The experimental data reported here was taken from a broadband Terfenol-D transducer developed at Iowa State University[6,9]. It was designed to produce an output free of spurious resonances, and to allow adjustable prestress and magnetic bias. A two inch long, quarter inch diameter laminated Terfenol-D rod ($Tb_{0.3}Dy_{0.7}Fe_{1.9}$) was placed inside two coils, an inner single layer 110 turn pick-up coil, and a multi-layer 1100 turn drive coil. A current control amplifier (Techron 7780) provided the input to the drive coil which produced the applied AC magnetic field and a DC magnetic bias as needed. Additional magnetic bias was provided by a slit, cylindrical permanent magnet which surrounded the coils. Washers in series with the Terfenol-D rod provided a mechanical prestress, which could be varied with a prestress bolt which threaded into the base and pushed the rod into the washers. The measurable quantities from the transducer included the current and voltage in the drive coil, voltage induced in the pick-up coil, and the mechanical output. A Lucas LVM-10 LVDT (linear variable differential transformer, a displacement sensor based on a changing reluctance) was used to measure the displacement of the transducer for the strain versus applied magnetic field plots. For the swept sine tests, a PCB model U353B16 accelerometer (2.5 gm) was attached to the top of a 115 gm load on the output of the transducer to measure the acceleration. The material properties were determined from an impedance analysis with data collected using a swept sine. The model and procedure is described in detail in the references[8,9].

5. QUASI STATIC PERFORMANCE

Investigation of the effect of prestress on transducer performance begins with the measurement of the strain versus applied field under quasi-static conditions. The prestress was applied to the rod with the use of a washer assembly. As the rod was driven it did work against the washers, oscillating around the nominal prestress determined for each test. The washer assembly stiffness was 7170 lbs/in (1.256e6 N/m). During operation the prestress varied by 146 psi per mil displacement. The change in prestress computed from the peak displacement and the percentage change from the nominal value is given in Table 1 for each prestress at five different drive levels. The large change in prestress for the 1000 Oe tests, up to 40% from the nominal value, is a significant issue to consider in transducer design. For lower drive levels, used for the dynamic tests, the change in prestress is a more acceptable seven percent or less.

The transducer was driven with a 0.7 Hz, 1000 Oe (79.6 kA/m) AC applied magnetic field. The magnetostriction (strain ppm or $\mu\varepsilon$) was measured and plotted versus applied magnetic field H for five prestresses 0.5, 0.75, 1.0, 1.25, and 1.5 ksi in Figure 1. The measured strain was normalized so that the zero strain point coincided for all plots. No magnetic bias was applied so the magnetostriction is symmetric with magnetization and the two sided strain versus applied field or "butterfly" results. The strain shows a doubling of the applied field frequency.

Bias	25 Oe		50 Oe		75 Oe		100 Oe		1000 Oe	
psi	psi	%	psi	%	psi	%	psi	%	psi	%
750	13.9	1.85	29.2	3.89	43.8	5.84	54.6	7.28	306.0	40.0
1000	13.9	1.39	27.3	2.73	43.0	4.30	52.8	5.28	314.0	31.4
1250	14.7	1.18	28.8	2.30	42.2	3.38	51.9	4.15	292.7	23.4
1500	4.9	0.30	17.7	1.18	30.2	2.01	40.4	2.69	280.0	18.7

Table 1. Maximum change in prestress (0-peak) and change as a percentage of the nominal prestress during operation at resonance.

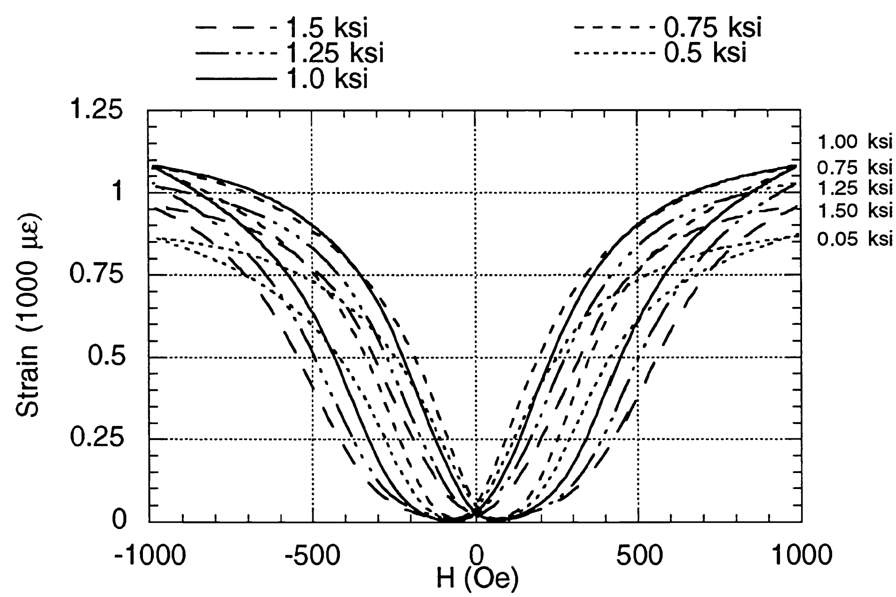


Figure 1: Strain versus applied field butterflies at 0.7 Hz for 0.5, 0.75, 1.0, 1.25, and 1.5 ksi.

The influence of prestress on near DC transducer output is seen in the strain, strain-field slope, and losses in Figure 1. The peak magnetostriction reached for each prestress at 1000 Oe increases from 860 $\mu\varepsilon$ at 0.5 ksi to a peak 1075 $\mu\varepsilon$ at 1.0 ksi and then decreases to 960 $\mu\varepsilon$ at 1.5 ksi. The region of highest slope or change in strain with applied field, also known as the burst region[10], shows a slightly different trend. The maximum slope increases from 2.2 $\mu\varepsilon$/Oe at 0.5 ksi to a nearly constant value 2.77 $\mu\varepsilon$/Oe at 0.75 and 1.0 ksi, then decreases to 2.44 and 2.17 $\mu\varepsilon$/Oe respectively at 1.25 and 1.5 ksi. As the prestress increases from 0.5 to 0.75 ksi the field at which the maximum slope occurs decreases from 310 to 275 Oe. For further increases in prestress 1.0, 1.25, and 1.5 ksi, the maximum slope occurs at larger applied fields, 400, 460, and 530 Oe respectively. As the prestress increases beyond 0.75 ksi, the burst region is reached at larger magnetic fields because more energy is required to overcome the prestress. The butterflies show hysteresis, with the trace following the lower leg up as the applied field is increased and the top leg down as the applied field is decreased. The amount of hysteresis, or loss in one cycle, is related to the area enclosed in the butterfly loop. The hysteresis increases with increasing prestress, significantly altering the path followed by the strain for the increasing and decreasing field.

The butterflies show the effect of prestress at zero magnetic bias. However, they do not adequately describe the difference in performance at various prestress. In addition to the problem of frequency doubling, AC operation at the higher prestresses around the zero magnetic bias point would be very inefficient for low to medium drive levels since the slope is so shallow in this region. By applying a DC magnetic bias field, AC operation can be moved to steeper regions of the quasi-static curve, eventually reaching the middle of the burst region, where much larger strains are realized for a given AC drive level. Note, however, that to avoid frequency doubling biased operation limits the maximum 0 to peak AC field to the magnitude of the DC bias. In order to examine the potential for interaction between prestress and magnetic bias, we next consider the effect of the magnetic bias on the quasi-static transducer performance under the varying prestresses.

6. QUASI-STATIC EFFECT OF PRESTRESS AND MAGNETIC BIAS

When a DC magnetic bias is applied to the Terfenol-D rod along with the AC magnetic drive field the strain-applied field loop changes shape. Figure 2 shows 1.0 ksi prestress at a DC bias of 150, 290, 415, 540, and 675 Oe (marked on each plot). In each test the 0.7 Hz AC drive level amplitude was set to the magnetic bias thus avoiding frequency doubling. The overall shape of the strain field plots change dramatically as the magnetic bias increases. Differences in the effective slope and peak displacement are seen as the magnetic bias is increased from 150 Oe to 415 Oe, which has the most symmetric shape, and then beyond to 675 Oe.

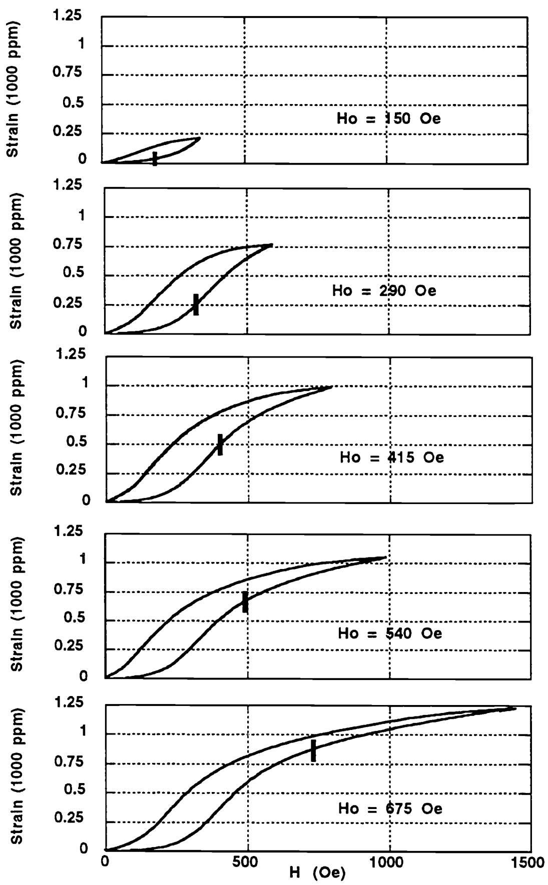


Figure 2: Strain versus applied magnetic field under 1.0 ksi prestress at 150, 290, 415, 540, and 675 Oe. Tick marks indicate magnetic bias Ho.

The choice of a magnetic bias for a given prestress is mentioned briefly in several studies[2,3,4]. However few details are given on the criteria used for determining an appropriate magnetic bias. The criteria given here, which has been used by the authors for other studies, is based on selecting an "optimized" magnetic bias for each prestress, which together define a bias condition. The "optimized" magnetic bias H_O is the bias which produces a symmetric or balanced strain-applied field relationship when operating the transducer to achieve the maximum output for a quasi-static 0.7 Hz input. The difference in output from a transducer with an "optimized" magnetic bias and an over bias or under bias is clear from the extreme difference in the strain plots in Figure 2.

The above criteria is met in the middle plot (415 Oe) in Figure 2. A current of approximately ±1.4 A, corresponding to an applied field of ±415 Oe around the initial magnetic bias identified with a vertical line, produces a displacement of ±25 microns (±500 micro strain) around the initial transducer output position (zero displacement). The magnetic bias was produced by the permanent magnet which had an effective strength of 150 Oe and the remainder made up by a DC current of 0.89 amperes through the drive coil, rated at 300 Oe/A. The value of H_O needed to obtain a symmetric strain-applied field relationship was determined for each of the four prestress levels and the results are shown in Table 2. Unless otherwise noted, when a prestress value is given it will refer to the prestress with the "optimized" magnetic bias as shown in Table 2.

The magnetic bias optimized with this quasi-static symmetric strain field method is over twice that used by Moffet et al. at the same prestress[2]. This highlights the importance of clearly defining the method used to determine the bias condition. In addition, other factors in the optimization equation, such as magnetic circuit architecture, prestress assembly, internal mechanical impedance, and external load impedance may also prove significant.

Plots of the quasi-static strain versus applied field for each prestress with the "optimized" magnetic bias (the AC drive level amplitude is equal to the magnetic bias Ho) are shown in Figure 4. Comparing the slopes of the increasing applied field leg, shows that the maximum slopes are identical for all prestresses over region C. A and B indicate regions over which the 1.25 and 0.75 ksi slopes match the maximum 1.0 ksi slope, respectively. 1.5 ksi shows a decidedly shallower slope above and below region C. The 1.0 ksi plot shows the highest slope for the largest change in strain. In contrast with the unbiased results (figure 1), an optimized bias results in the same maximum slopes for all prestress levels. This comparison points out the importance of biasing the Terfenol-D to allow operation centered on the burst region.

Bias Condition	1	2	3	4
Prestress	0.75 ksi	1.0 ksi	1.25 ksi	1.5 ksi
Magnetic bias (Oe)	300 Oe	415 Oe	480 Oe	540 Oe

Table 2: Bias conditions 1 through 4, magnetic bias for each prestress level optimized using the quasi-static symmetric strain field criteria.

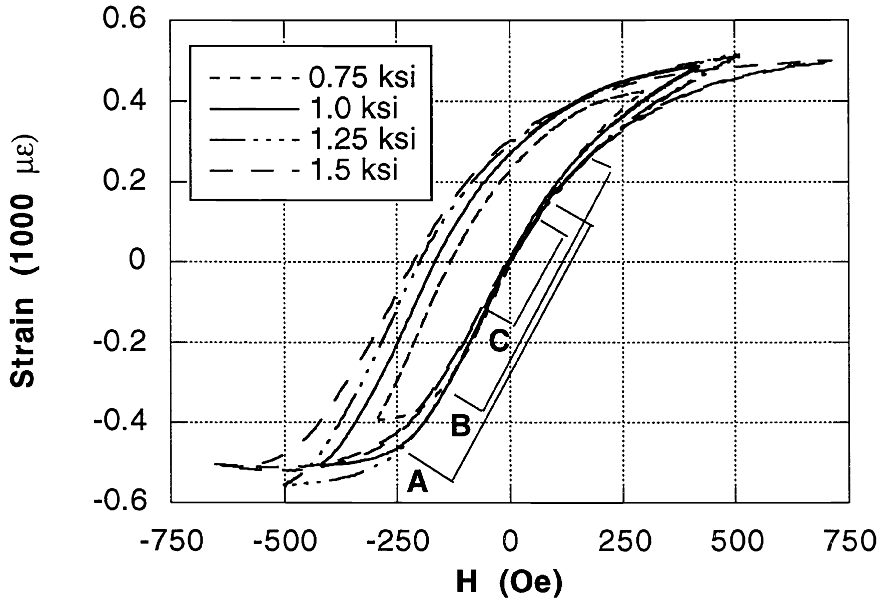
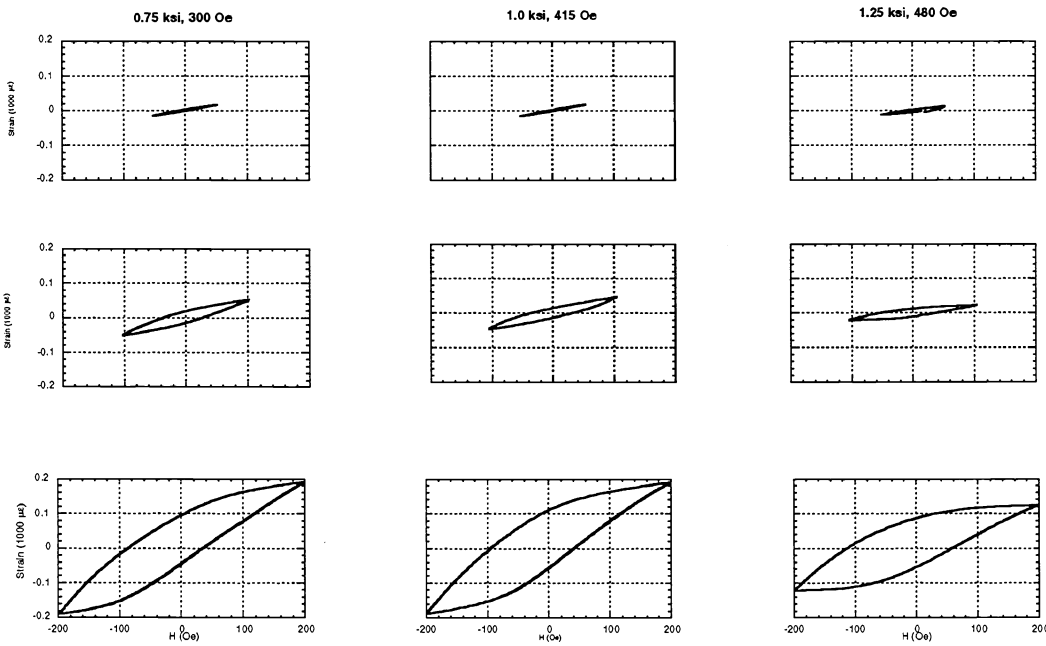


Figure 4. Strain versus applied field for the four bias conditions, (0.75 ksi, 300 Oe), (1.0 ksi, 415 Oe), (1.25 ksi, 480 Oe), (1.5 ksi, 540 Oe) centered around the DC magnetic bias and one half the total strain. A, B, and C indicate regions over which the 1.25, 0.75, and 1.5 ksi slopes match the maximum 1.0 ksi slope, respectively.

Operating a transducer with the same prestress at different magnetic biases results in quite different performance. This supports the conclusion of Moffet et al. that it is the "bias condition", both mechanical prestress and magnetic bias which must be considered. The method used to determine the magnetic bias in this study is based on the quasi-static optimization criteria of providing the most symmetric response over the largest possible output range. It may be possible to improve certain measures of transducer performance by optimizing the magnetic bias and prestress based on alternative criteria.

7. QUASI-STATIC EFFECT OF BIAS CONDITION AND DRIVE LEVEL

The effect of the bias condition at different drive levels was investigated by measuring the strain versus applied magnetic field at 0.7 Hz for a series of drive levels up to the magnetic bias. Figure 5 shows nine minor loops with increasing AC drive level from top to bottom: 50, 100, and 200 Oe. The figures, from left to right, are at bias 1 (0.75 ksi, 300 Oe), bias 2 (1.0 ksi, 415 Oe), and bias 3 (1.25 ksi, 480 Oe), respectively. At each bias condition the slope of these minor loops increases with increasing drive. Comparison of a given drive level across bias conditions shows the nominal slope of the quasi static loops decreases with increasing stress. For example, the slope of the 100 Oe loops (middle row) is seen to decrease slightly from 0.44 με/Oe at 0.75 ksi to 0.43 με/Oe at 1.0 ksi and then more sharply to 0.24 με/Oe at 1.25 ksi. This is in contrast with the large drive quasi-static plots seen in Figure 4, which shows the same peak slope for all prestresses. These results lead us to the conclusion that the large field strain versus applied field plots, with or without magnetic bias, do not provide all the information we need to optimize performance of a transducer with prestress.



Figures 5: Strain vs. H at 0.7 Hz for prestress increasing from left to right: bias 1 (0.75 ksi 300 Oe), bias 2 (1.0 ksi 415 Oe), and bias 3 (1.25 ksi 480 Oe), and AC drive level, increasing from top to bottom: 50, 100, and 200 Oe.

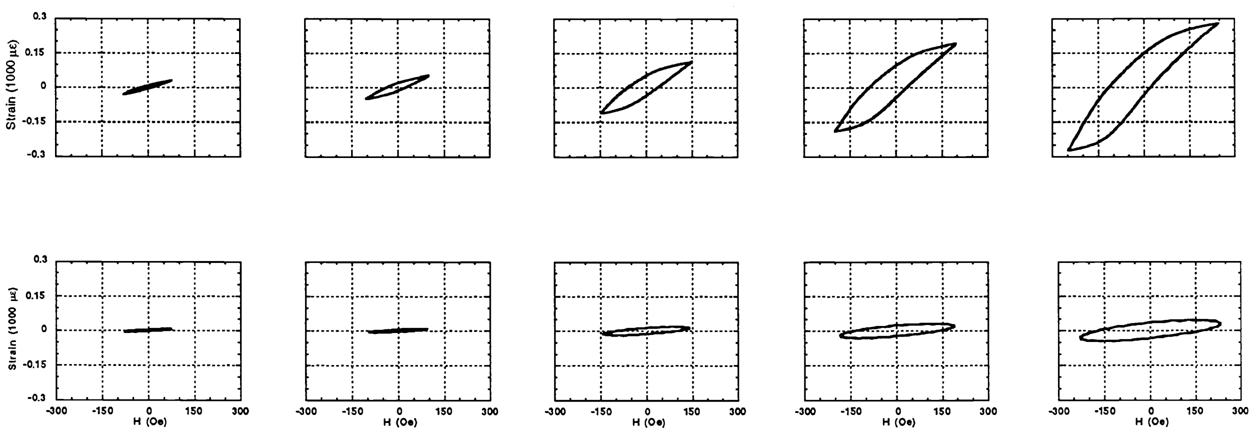


Figure 6: Strain versus H for bias condition 1 (0.75 ksi, 300 Oe) at 0.7 Hz (top set) and 400 Hz (bottom set), AC drive level amplitude increasing from left to right: 75, 100, 150, 200, 250 Oe.

H (Oe) Freq.	25	50	75	100	150	200	250
0.7 Hz	0.303	0.330	0.393	0.502	0.757	0.963	1.117
400 Hz	0.060	0.065	0.078	0.088	0.125	0.152	.203

Table 3: Comparison of nominal strain per applied field (με/Oe) at 0.7 Hz and 400 Hz calculated from minor loops under bias condition 1 (0.75 ksi, 300 Oe).

8. DYNAMIC VERSUS QUASI-STATIC PERFORMANCE

Next we consider whether the effect of the bias condition (prestress and magnetic bias) varies from quasi-static to dynamic operation. A frequency of 400 Hz, well below resonance, was picked for the tests. The displacement was measured with the LVDT at various applied magnetic fields for all bias conditions. The plots in Figure 6 show strain vs. H for increasing drive level (left to right) under bias condition 1 (0.75 ksi 300 Oe) at 0.7 Hz (top set) and 400 Hz (bottom set). Both sets of minor loops exhibited an increase in slope with increasing drive level. Comparison between the two sets of plots shows that the dynamic performance differs radically from the quasi-static in shape and slope. The nominal slope is computed from the line connecting the two extreme points. The slope of the 400 Hz plots has decreased considerably compared to the 0.7 Hz plots, as summarized in Table 3. Similar results were obtained at the other three bias conditions, with a decrease in the slope between the 0.7 and 400 Hz tests, as was observed in Figure 6. This motivates the analysis of material and transducer behavior under dynamic conditions.

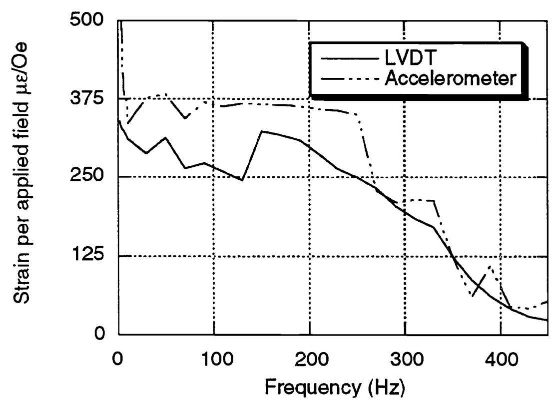


Figure 7a Strain rate with applied field versus frequency for 0.75 ksi at 300 Oe drive level.

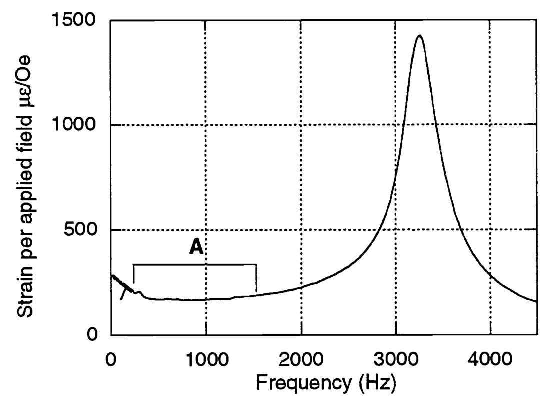


Figure 7b Typical strain rate with applied field versus frequency.

Evaluating the strain per ampere as a function of frequency shows the influence of AC losses and mechanical resonance on the strain output. Figure 7a shows the strain per ampere for bias 1 (0.75 ksi, 300 Oe), with a drive of 100 Oe from 1 to 450 Hz. Measurements were made simultaneously with a PCB model UJ353 accelerometer (30 gm) and the LVDT. The dramatic decrease in strain per applied field seen in Figure 6 is also seen here. Figure 7b shows a typical strain per applied field versus frequency, beyond the first mechanical resonance of the system, which was set at 3300 Hz. The strain per Oe decreases in the stiffness controlled region due to increasing AC losses. At higher frequencies the mechanical resonance causes the strain per ampere to increase dramatically to much larger values than the quasi-static case. The sum of these two effects can result in a fairly constant value of strain per Oe as seen in region A of Figure 7b. The average value of the strain per applied field in this region, the dynamic strain coefficient, will be presented in section 10.5. Until a model is developed to describe the relation between the quasi-static and dynamic performance which includes the influence of the resonance and AC losses, dynamic measurements at the operating frequency must be made.

9. DYNAMIC TESTING: IMPEDANCE ANALYSIS

One means of ascertaining the effect of the bias condition and drive level on transducer performance is to analyze the input electrical impedance versus frequency. This is accomplished using a swept sine excitation over the bandwidth of operation and measuring the input current and voltage at discrete frequency intervals. The impedance functions contain a wealth of knowledge relating to the transduction process and therefore quite naturally show the effect of different operating conditions. The electrical impedance function, voltage across the drive coil over current impressed on the coil, is the sum of the blocked impedance and the mobility impedance. The blocked electrical impedance, meaning the impedance measured if the mechanical side was clamped, shows variation with drive level and prestress. The bode plot of the total impedance versus frequency are shown in Figure 8a for bias 1 (0.75 ksi) at drive 25, 50, 75, and 100 Oe, and in Figure 8b for 100 Oe drive for bias 1 to 4 (prestresses of 0.75, 1.0, 1.25, and 1.5 ksi). As the drive level is increased the slope of the blocked impedance increases; whereas as the prestress is increased the slope decreases. The mobility impedance, seen as a peak and valley change from the blocked impedance, contains information from the mechanical side which has been transduced into the electrical impedance. In general, the frequency of the peak in the impedance, often referred to as the resonance at constant applied field, decreases with increasing drive and increases with increasing prestress.

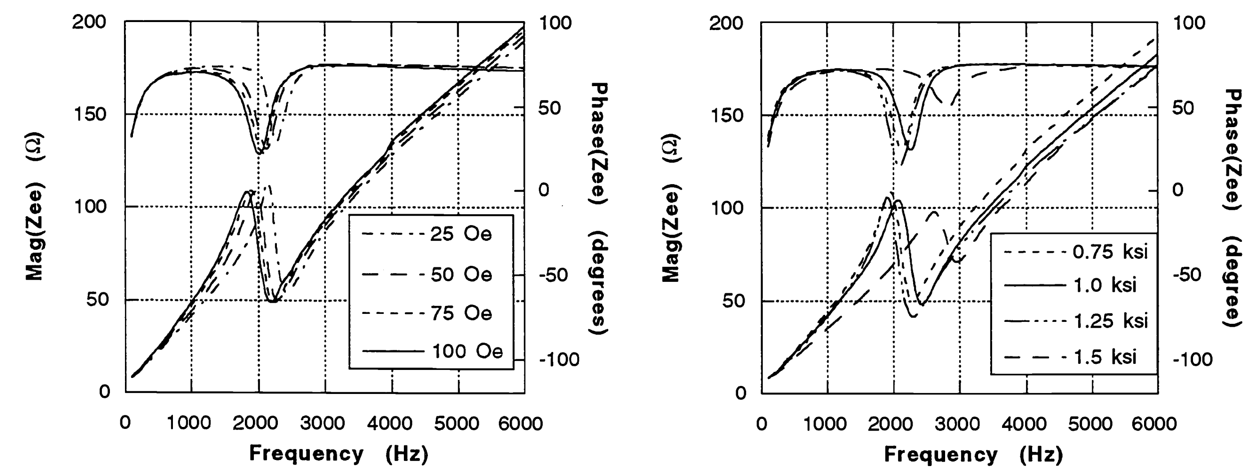


Figure 8a and b: Total electrical impedance versus frequency a) for 0.75 ksi, 300 Oe biasa, atfour drive levels, 25, 50, 75, and 100 Oe, and b) for 100 Oe drive at bias 1 to 4 (0.75, 1.0, 1.25, and 1.5 ksi).

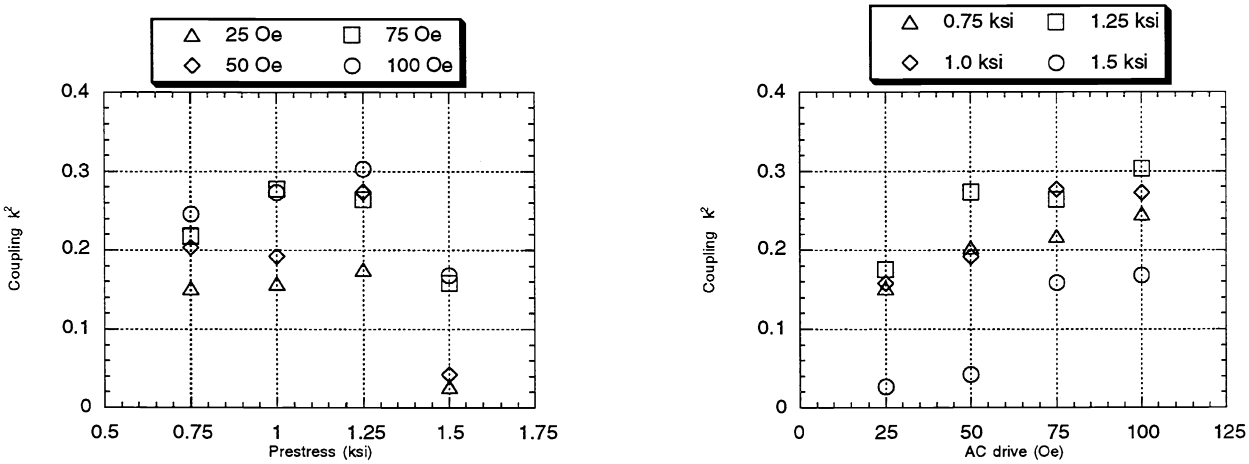
10. DYNAMIC MATERIAL PROPERTIES

Impedance analysis provides us with a method of characterizing the performance of the transducer and magnetostrictive core under dynamic operating conditions. Data obtained from swept sine transducer measurements are reduced using the magnetostrictive constitutive equations, transduction equations, and a mechanical model of the transducer as described in detail in the references[8,9]. The electrical impedance and admittance mobility loops are used to determine the resonant, anti-resonant, and half power point frequencies. The acceleration per ampere frequency response functions are used to determine damping and average displacement per ampere in the dynamic region of operation discussed in section 8. Young's Modulus E_y^H, magnetomechanical coupling k^2, permeability at constant stress μ^σ, dynamic strain coefficient q, and mechanical quality factor Q_m, can then be calculated using this data and readily measurable transducer and Terfenol-D rod parameters. For each bias condition, data was collected at four drive levels, 25, 50, 75, and 100 Oe. Figures 9 through 13 show these five properties versus prestress and versus drive level. Variations in prestress at each drive level from Table 1 should be kept in mind. However, since the maximum change in prestress is 7 percent or less in all cases, data in this paper will not be shown with error bars.

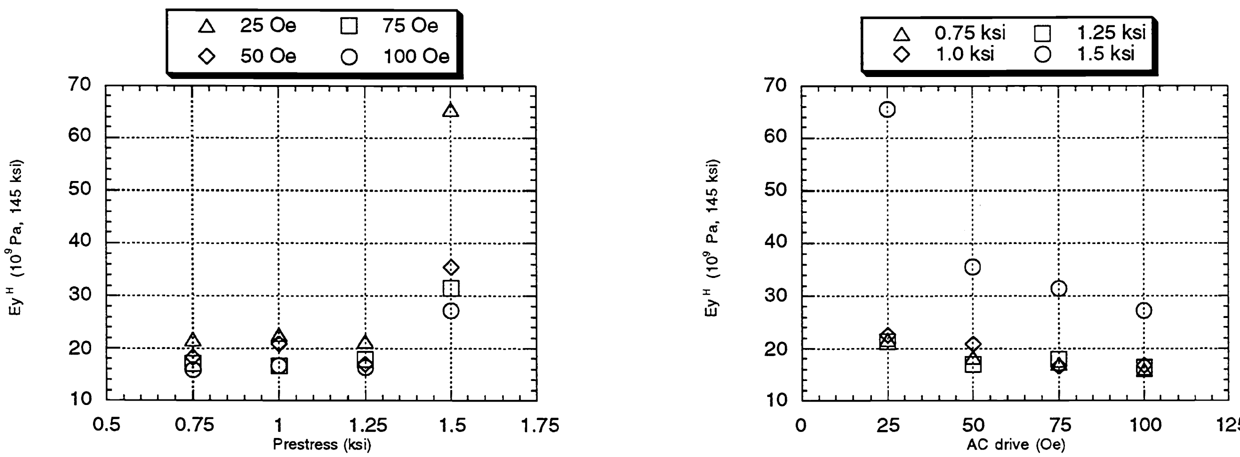
10.1 MAGNETOMECHANICAL COUPLING FACTOR

The magnetomechanical coupling provides a measure of the transduction efficiency of the Terfenol-D core; it is the ratio of the stored mechanical energy to the energy stored in the magnetic field. In Figure 9a the coupling shows a gentle increase with prestress to a maximum value at a prestress of 1.25 ksi for all drive levels. At 1.5 ksi the coupling falls off rapidly. In figure 9b the coupling increases as the drive level is increased for all prestresses.

These effects can be explained by considering the effect of prestress and drive level on the available magnetic energy and output mechanical energy. The increase in coupling with prestress from 0.75 to 1.25 ksi is a result of the preferential initial magnetic state of the material which leads to an increased magnetization capability. One aspect of the improvement in performance due to the initial magnetic state was seen in the quasi-static butterflies of Figure 1, where the output peaked at 0.75 to 1.0 ksi. Beyond the 1.25 ksi bias the coupling decreases as the additional energy required to overcome the mechanical prestress increases and is no longer available for transduction.



Figures 9a and b: Magnetomechanical coupling versus (a) prestress and (b) drive level.



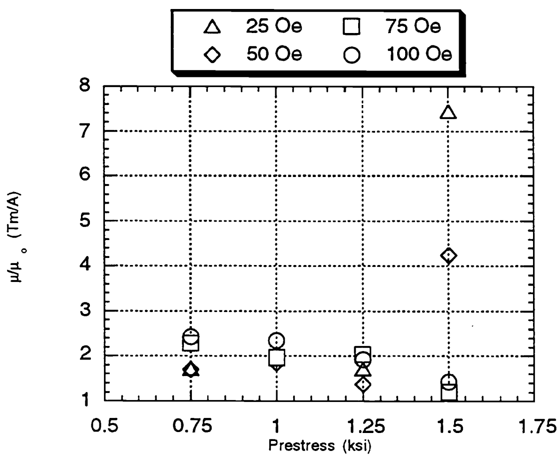
Figures 10a and b: Young's Modulus at constant applied magnetic field versus a) prestress and b) drive level (6.89 MPa = 1.0 ksi).

10.2 YOUNG'S MODULUS

Young's Modulus provides us with an important design parameter, the stiffness of the Terfenol-D material. In Figure 10a and b Young's Modulus measured at a constant applied field remains relatively constant around 15-20 GPa (2150-2900 ksi) for all drives at prestresses of 0.75, 1.0, and 1.25 ksi. At 1.5 ksi, E_y^H increases to around 30 GPa (4355 ksi) for the 50, 75 and 100 Oe drive levels and doubles to 65 GPa (9433 ksi) for 25 Oe. One explanation for this may be that the 25 Oe drive did not provide enough energy to overcome the prestress energy, thus resulting in little magnetostriction and a relatively stiff system. This is also suggested by the low magnetomechanical coupling in Figures 9a and b. E_y^H decreases with increasing drive level, most noticeable in the 1.5 ksi data. This is in agreement with earlier published data which shows the ΔE effect increasing with drive level, hence a decreasing Young's Modulus with increasing drive level at low drive levels[10-12].

10.3 PERMEABILITY

The permeability at a constant stress, measured from the three parameter method, is a gauge of the magnetic induction B generated in the Terfenol-D core when subjected to an applied magnetic field. Figure 11a shows different trends with increasing prestress between the lower (25 and 50 Oe) and upper (75 and 100 Oe) drive levels. The later decrease uniformly with increasing prestress, while the former appear to increase abruptly at a prestress of 1.5 ksi. The higher drive levels have the expected trend since with increasing prestress to overcome, a given applied field will produce less magnetostriction. Thus less of a given applied field goes into magnetization of the Terfenol-D core. The permeability versus drive level in Figure 11b shows a slight increase with increasing drive level for the lower three prestresses. This trend is in contrast with results at lower drive levels and masses reported by the authors[12], however the differences can be explained by the sensitivity of the permeability trends to operating conditions. The different trend exhibited by the 1.5 ksi data which starts at very high values for 25 and 50 Oe, reaches a minimum at 75 Oe and then increases at 100 Oe, is attributed to the high prestress dominating the transduction process.



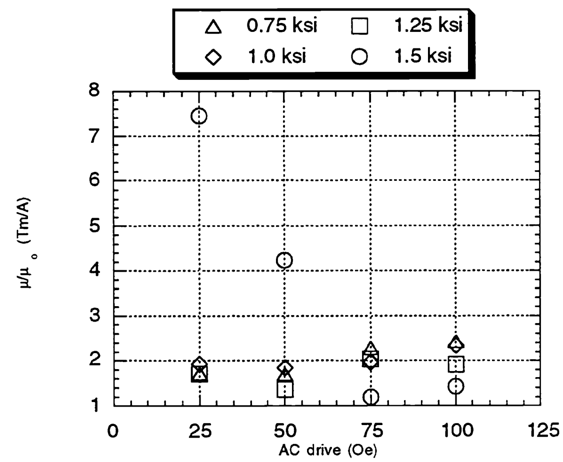


Figure 11a and b: Permeability at a constant stress versus a) bias condition and b) drive level.

10.4 MECHANICAL QUALITY FACTOR

The mechanical quality factor is a measure of the transducer's overall system damping (inversely proportional to mechanical losses) and also provides a magnification factor for operation at resonance. Q_m is shown versus prestress and drive level in figures 12a and b. In general, Terfenol-D transducers have high damping (they are low Q) relative to piezoceramic material transducers. Recall from the previous sections that the 25 Oe, 1.5 ksi test shows the least transduction of all cases and appears the least energized. Here the lowest drive level Q_m is relatively large, indicating less system damping below some nominal level of magnetostrictive transduction. Above that level slow increases in damping occur with both increasing drive and prestress. Thus although the area enclosed by the quasi-static strain versus applied field loops in figures 3, 4, and 5 increased with both increasing prestress and drive level, Q_m measured dynamically does not reflect this increasing energy loss trend in all cases. Notably, the 25 Oe tests reflect a decrease in losses, higher Q_m, with increasing prestress.

10.5 DYNAMIC STRAIN COEFFICIENT

The dynamic strain coefficient q is a measure of the strain produced for an AC magnetic field; it is the instantaneous slope of the strain versus applied field plot for harmonic operation. The dynamic strain coefficient, given here as one number, is an average of the strain per applied field from approximately 100 to 600 Hz. Therefore it is not the slope of the strain versus applied field plot at a particular operating frequency but a system parameter for the operating conditions of the test (transducer load, temperature etc.) below resonance. As shown in section 8 it may differ greatly from the strain per applied field measured under quasi-static conditions.

Figure 13a shows q versus prestress. Similar to the coupling, q has a peak around 1.0 to 1.25 ksi and a noticeable decrease at 1.5 ksi. As with the coupling this results from the preferential magnetic state of the material introduced by the mechanical prestress. The distinct difference in q versus drive level at 1.5 ksi is also seen in Figure 13b. Clearly additional prestress reduces the transduction, less of the input electrical energy is delivered to the load. q increases fairly linearly with increasing drive and the slope of this line, the change in q with H, is fairly constant for 0.75, 1.0, and 1.25 ksi. The 1.5 ksi tests show the same increase in q with drive level but at half the value of the lower prestresses. These dynamic results contradict the analysis of the slope of the quasi-static strain with applied field discussed in section 7, which shows that at 100 Oe drive the maximum slope of all prestress cases is nearly constant. This reinforces the importance of dynamic measurements as discussed in section 8.

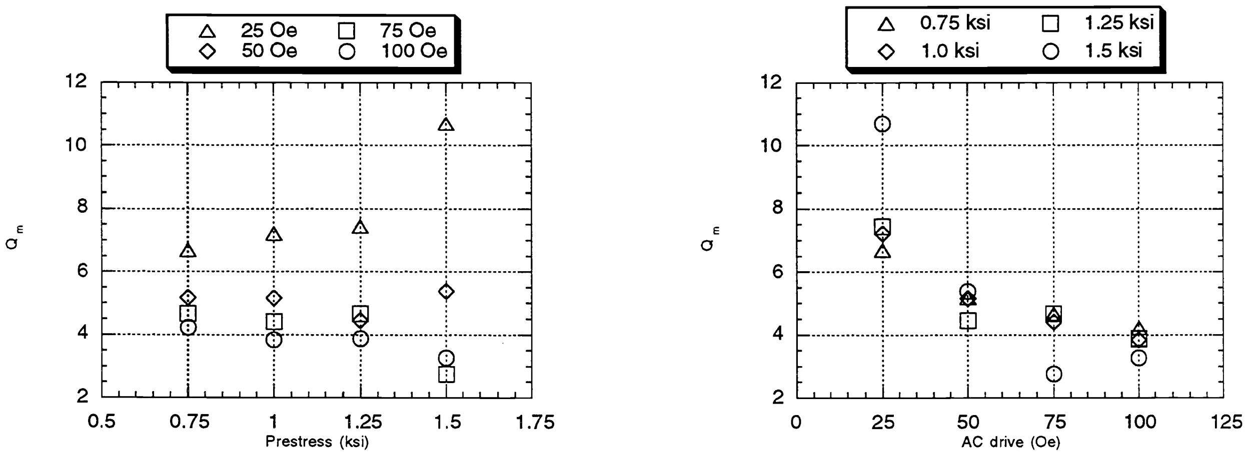


Figure 12a and b: Mechanical quality factor versus a) prestress and b)drive level.

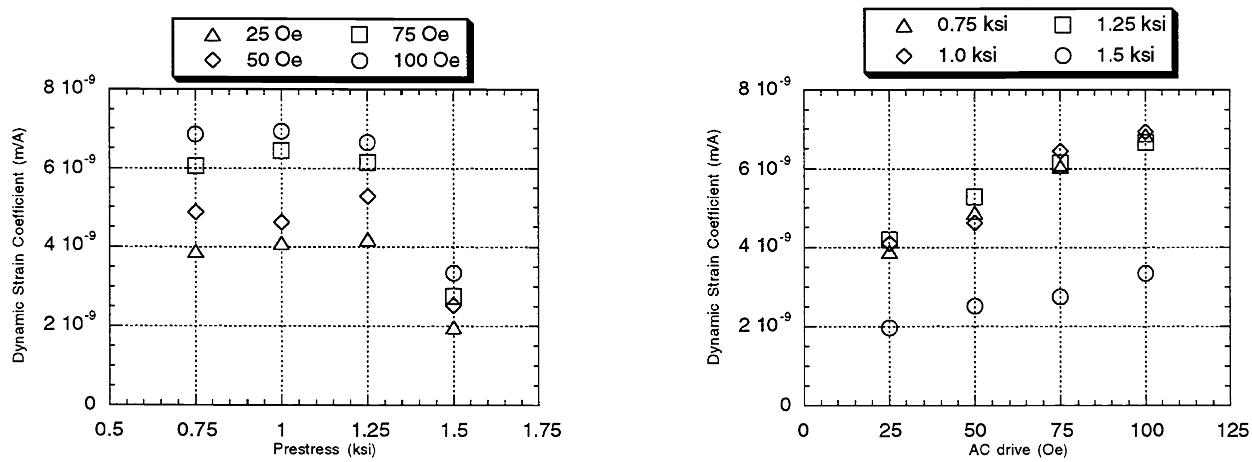


Figure 13a and b: Dynamic strain coefficient q versus a) prestress and b) drive level.

10.6 MATERIAL PROPERTY TRENDS AND OPTIMIZATION

Trends in the properties with prestress and drive level are indicated. A peak in coupling and dynamic strain coefficient with prestress is seen at 1.0 to 1.25 ksi. Young's Modulus shows a slight increase with increasing prestress, in particular beyond 1.25 ksi, and a decrease with increasing drive level (the ΔE effect). The material properties at a prestress of 1.5 ksi, particularly the 25 and 50 Oe drive levels, show distinct differences in trends for mechanical quality factor and permeability from the rest of the tests. These differences are attributed to insufficient energy input; too low of a drive level to overcome the mechanical prestress. This also results in an extremely low coupling and dynamic strain coefficient, and a higher

Young's Modulus and mechanical quality factor. Additional general trends were observed in the properties versus drive level. The dynamic strain coefficient and magnetomechanical coupling increased with increasing drive level, while the Young's Modulus and mechanical quality factor decreased with increasing drive level. These trends can be summarized in another way: as the Terfenol-D is energized it appears less inert and more magnetostriction results, thus the coupling, strain coefficient, compliance, and damping increase.

The peaks in coupling and dynamic strain coefficient indicate that it should be possible to optimize the transducers performance with prestress. For the operating conditions used in these tests (120 gm load, 20-30 ° C, 7170 lbs/in prestress mechanism, drive levels 100 Oe and below) this broadband transducer can be operated with a peak magnetomechanical coupling of 0.2 to 0.3 at 1.25 ksi prestress, 480 Oe magnetic bias. The peak strain coefficient is more sensitive to drive level reaching a peak of 4.0 to 6.0 nm/A between 1.0 ksi prestress, 415 Oe magnetic bias and 1.25 ksi, 480 Oe magnetic bias.

11. CONCLUSIONS

The effects of prestress, magnetic bias, and drive level on the performance of a Terfenol-D transducer are examined under quasi-static and dynamic conditions. The effect of the magnetic bias on the strain versus applied field plot is examined and its influence on the output at a given prestress level is demonstrated. Quasi-static strain versus applied field plots at high drive levels show differences in trends with prestress when an optimal magnetic bias field is applied. At low drive levels (less than 300 Oe) the strain versus applied field slope decreases sharply above 1.25 ksi prestress, in contrast with the large field results. The most important result shown here is the difference between the quasi-static and dynamic performance of the transducer. Large reductions in the strain versus applied field slope, up to 80%, from operation at 0.7 Hz to 400 Hz is observed. The dynamic response of the transducer can be explained as the interaction between the frequency dependent AC losses and mechanical resonance. The total electrical impedance is shown to provide a means of examining the effect of the prestress and drive level on the transducer's performance. Trends in the material properties with prestress and drive level are noted, including peaks in the coupling and dynamic strain coefficient at 1.0 to 1.25 ksi. Further work is needed to clearly identify the prestress and magnetic bias which optimize coupling and axial strain coefficient.

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