

Statistical analysis of Terfenol-D material properties

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ABSTRACT

Modeling of magnetostrictive Terfenol-D transducer performance requires reliable data on functional trends of the magnetostrictive element's material properties under various operating conditions. A statistical study was designed to experimentally evaluate material properties of 50 Terfenol-D samples under varied mechanical loads, varied AC drive levels, magnetic bias and mechanical prestress typical of transducer applications. This approach is based on a low-signal, linear-magnetomechanical model of the test transducer, and electroacoustics theory. Statistical analysis is provided for the material properties: Young's modulus at constant applied magnetic field, linear coupling coefficient (or axial strain coefficient), magnetomechanical coupling factor, and magnetic permeability at constant strain. Functional relations between material properties and AC drive levels and loads are developed, and corresponding confidence intervals are assessed. The trends show the sensitivity of Terfenol-D material properties to the operating variables and highlight the importance of properly understanding the effects of operating conditions on transducer performance.

Keywords: Terfenol-D, magnetostriction, transducer

1. INTRODUCTION

Terfenol-D ($\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_y$) is a highly magnetostrictive alloy of the rare earth elements terbium and dysprosium with the 3d transition metal iron. The name Terfenol-D derives from the composition of the material (Ter \rightarrow terbium, Fe \rightarrow iron, D \rightarrow dysprosium) and the place where the alloy was originally developed, the Naval Ordnance Laboratory (NOL, now NSWC). Terfenol-D exhibits nominal magnetostriction coefficients along principal crystallographic directions of $\lambda_{111} = 1600 \times 10^{-6}$ and $\lambda_{100} = 90 \times 10^{-6}$ [1]. Bulk saturation magnetostriction well in excess of 2000×10^{-6} is achievable when Terfenol-D is subjected to proper compressive stress along the unique axis. This compressive stress has the effect of (randomly) aligning magnetic domains in the direction perpendicular to the unique axis in the demagnetized state, thus producing an improvement in saturation magnetostriction [2, 3]. When used as a transducer driver element, Terfenol-D is capable of generating large oscillatory strains under the application of AC magnetic fields, a magnetic bias, and a mechanical prestress. This oscillatory motion can be used to drive external loads in a vast array of applications such as noise and vibration control of structures, micro-positioning devices, surgical tools and linear motors, among others.

Although there have been important research efforts devoted to characterizing quasi-static properties of raw Terfenol-D material, fundamental information on material properties of Terfenol-D as used in transducers is scarce. 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, magnetic bias, applied magnetic field or drive level, external load, and temperature. Transducer models that incorporate the effects of all operating parameters simultaneously are not currently available, in part because reliable models of the functional dependence

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of fundamental material properties such as permeability and elastic modulus on variable operating parameters have not been developed yet. Transducer designers need to be able to understand such trends, and to recognize which trends are predictable with various operating conditions. Obtaining reliable information on trends requires the ability to obtain a statistically significant data base on material properties under controlled operating conditions. The collection of experimental data in a statistical frame-work aids in the better understanding of those trends because it allows rigorous assignment of confidence and prediction intervals (“error bars”) to the fitted data.

Prior studies (Ref. [4, 5]) report experimental evidence of significant variation in material properties of samples subjected to repeated tests under identical operating conditions. The question arises as to whether these variations are due solely to the stochastic nature of magnetostriction or to a combination of stochastic phenomena *and* external factors associated with a less-than-perfect control of the operating variables: drive level, mechanical prestress, magnetic bias, transducer and Terfenol-D element temperatures, and mechanical load. Meaningful answers can only be provided after formal statistical evaluation of experimental data of Terfenol-D samples subjected to repeated testing.

In view of these considerations, work was undertaken with the goal of identifying trends and inherent uncertainties in the functional dependence of fundamental elasto-magnetic properties of Terfenol-D on changes in operating conditions in a controlled transducer environment. The experimental approach used is based on a low signal, linear magnetostriction model, a linear transduction model, and a lumped mass-spring-damper mechanical model of the test transducer. Electrical impedance and admittance and acceleration per unit current complex functions are measured using a swept sine excitation at varied applied magnetic field strengths. A total of 50 Terfenol-D samples (30 solid, 20 three-laminate) are characterized in randomized performance tests to obtain the material property information. The study focused on three different test modalities:

- i. drive amplitude sensitivity;
- ii. test-to-test repeatability;
- iii. mass load sensitivity.

These data sets demonstrate the dependence of material properties on applied magnetic field levels and mass load and provide a preliminary assessment of the functional dependence of material properties on operating conditions in a transducer environment. When judiciously used, these results should facilitate more realistic modeling and design of Terfenol-D transducers and enhance the ability of designers to optimize transducer performance for specific dynamic applications.

2. METHODS

2.1 Terfenol-D material

A total of fifty 0.25" (6.35 mm) diameter, 2.02" (51.3 mm) long cylindrical samples (rods) produced via the free stand zone melt technique (FSZM) were tested. Two types of $Tb_{0.3}Dy_{0.7}Fe_{1.9}$ samples were studied: 30 solid rods and 20 three-laminate rods. The material was pre-screened according to measured near-DC output strain at 500 Oe (39.79 kA m^{-1}), no magnetic bias, and 1 ksi (6.9 MPa) mechanical prestress and assigned one of three classifications. High strain samples exhibited strains of more than 1200×10^{-6} ; average strain samples exhibited strains of 1000×10^{-6} to 1200×10^{-6} ; and low strain samples exhibited strains of less than 1000×10^{-6} . Ten samples of each rod type were randomly selected for use in this study. Table 1 shows material classification.

Table 1: Classification of tested material.

	Average	Low	High
FSZM - solid, 0.25" \times 2.02"	A	B	C
FSZM - 3 laminates, 0.25" \times 2.02"	D	E	

2.2 Transducers and testing environment

Four identical transducers were built for the purpose of this study. These transducers are broadband laboratory units designed to facilitate backing out of rod material property information from measured data. The Terfenol-D

sample is placed inside a solenoid consisting of an innermost single-layered sensing coil and a multi-layer drive coil. A slit cylindrical permanent magnet surrounds the solenoid and provides most of the required magnetic bias. A bolt located in the transducer’s base pushes the Terfenol-D sample against two spring washers in the transducer head to provide the mechanical initial prestress, which for the purpose of this study was set to 1 ksi. Proper force-displacement calibration of the spring mechanism allows prestress adjustment by turning the bolt until the corresponding displacement is measured at the transducer output. Additional experimental details are provided in *Dapino et al.* [6].

An initial magnetic bias H_0 was selected for each transducer-rod combination based on criterion of providing a balanced or symmetric strain-applied field relationship approaching $\pm 500 \times 10^{-6}$ when driving the transducer at magnetic fields of $\pm H_0$ (± 280 Oe nominal) at near-DC (0.7 Hz) frequencies.

2.3 Material properties calculation

The measured quantities from the transducers include the drive coil voltage and current, the sensing coil voltage, and the transducer output acceleration. Resonance frequencies are identified from complex electrical impedance and admittance functions to determine the Young’s modulus at constant applied field, E_y^H , and the magnetomechanical coupling factor, k . Acceleration per unit current data from the stiffness controlled portion of mechanical output is used to obtain an average axial strain coefficient, q . The permeability at constant strain (μ^ϵ) in the stiffness controlled region of transducer performance is then calculated from these quantities. Ref. [6, 7] cover further details on the magnetostrictive, the electroacoustics, and the transducer models used for calculation of material properties.

2.4 Test modalities

The material characterization study was divided in three different test modalities. In all cases, transducer temperature was held between 20-30 °C. The three groups of tests are summarized as follows:

i) Drive amplitude sensitivity. Trends in fundamental elasto-magnetic properties of Terfenol-D under varied applied fields are investigated for ten samples of each rod type. From these trends, functional relations are developed based on statistics principles. These “baseline” tests used a mass load approximately equal to four times the nominal mass of the rod (60 grams). Sinusoidal drive amplitudes (zero to peak) of 2, 5, 10, 20, and 50 Oe (0.16, 0.4, 0.8, and 3.98 kA m⁻¹) were used to excite the transducer. Transducer-balanced experimental matrices (except for rod type A) were assembled by random assignment of the four transducers to each rod-drive level combination. Blocks of 50 rod-transducer assemblies and measurements for each rod type were run sequentially: A through E.

ii) Test-to-test repeatability. Unlike the baseline study, which is designed to observe variations in measurements in different rod-transducer combinations under varied drive levels, the repeatability study investigates the amount of variation in measurements taken at a fixed drive amplitude in an assembled rod-transducer pair. This variation is referred to as the sampling error. Rod-transducer pairs were assembled and cycled through 8-10 consecutive test repetitions at a fixed drive level before moving on to assembly and test of the following set of rod-transducer-drive level combination. Within rod type A, three samples were selected as best, average and worst in terms of near-DC maximum strain. Tests with a load of 60 grams were repeated ten times at drive levels of 5, 10, 20, and 50 Oe. These procedures underwent a slight revision for the B-E rod types. Four samples were used instead (worst, best and two average performing based on near-DC maximum strain), for a total of 16 rod-drive level combinations per rod type. The four transducers were assigned to each rod-drive level combination in a Latin Square fashion. Each measurement was repeated eight times. Rod-transducer combinations were fixed for a set of three mass load tests. Blocks of 16 sets of measurements (12 for rod type A) were run sequentially for rod types A through E.

iii) Mass load sensitivity. Information on variation of properties with transducer load was obtained using for each rod type the best, worst and two average performing rods in terms of near-DC maximum strain. As in the repeatability study, only three rod type A samples were tested. The three loading conditions used were: four times the nominal mass of the rod (60 grams), twice the nominal mass of the rod (30 grams), and no load (accelerometer mass only, ≈ 1.5 grams). Drive levels of 5, 10, 20, and 50 Oe were used, and transducers were assigned in a similar fashion as in the repeatability study. Blocks of 16 measurements (12 for rod type A) were run sequentially for rod types A through E.

2.5 Statistical analysis

Three main factors are controlled in the baseline and test-to-test repeatability studies: rods, transducers, and drive levels. The external mass is an additional participating factor in the mass load sensitivity study. Other operating parameters such as magnetic bias, mechanical prestress and transducer temperature remain unchanged following above mentioned criteria. These factors are, then, “constant”.

There are two parts to the statistical analysis. First, the effects of factors are identified by performing ANOVA analyses to each of the material properties. Due to the experiment being unbalanced with respect to all factors considered together¹, Type III sums of squares are performed instead of the usual Types I and II [8, 9]. The group of ten samples in each rod type constitute a random sample from the population of like rods. The effects of rods are thus random, which allows the extrapolation of results from the random sample to the whole population of similar rods. On the other hand, the effects of transducers and drive levels are treated as fixed.

In a second stage, a statistical model is considered which takes the general form (ignoring factor interactions):

$$Y_{ijk} = \tau_i + \rho_j + f(H_k) + \varepsilon_{ijk}$$

where τ_i represents the fixed effect of the i th transducer, ρ_j represents the random effect of the j th rod, $f(H_k)$ represents the functional dependence of Y on drive level H_k and ε_{ijk} is a random component attributed to experimental error. Depending on the relative weight of rods and transducers in the model in each particular case, these effects may be dropped from the model either individually or simultaneously. Since rods have a random contribution to the measurements, the variance of the model is $Var(Y) = \sigma_\rho^2 + \sigma^2$. Confidence and prediction intervals are computed from the reduced model in which the effect of rods and transducers are assumed to have no statistical significance.

A more thorough discussion on the statistical analysis of the present study is given in Ref. [10].

3. RESULTS AND DISCUSSION

The results presented here are separated in three sections following the three different test modalities: the baseline study, the test-to-test repeatability study, and the mass load sensitivity study. The analysis focuses on four properties:

- Young’s modulus at constant applied field, E_y^H ;
- axial strain coefficient, q (or d_{33} constant);
- magnetomechanical coupling, k ;
- permeability at constant strain, μ^ϵ .

3.1 Baseline study

Data from the laminated average material (type-D rods) will be used to demonstrate the steps taken in obtaining results from the experimental data. Evaluation of Young’s modulus at constant applied field as a function of applied field data in Figure 1 suggests a quadratic model may be appropriate to fit the measurements. Letting $\mu(H)$ be the mean response at drive level H , a possible model for the mean values is

$$\mu(H)/10^9 = \beta_0 + \beta_1 \log(H) + \beta_2 [\log(H)]^2$$

where β_i are the coefficients of the second-order logarithmic model. The approximately constant spread allows fitting the model to the data by the least squares method, which yields

$$\hat{\mu}(H)/10^9 = 57.01 - 3.71 \log(H) - 4.48 [\log(H)]^2$$

¹Each rod type was assigned its own experimental matrix. Except for rod type A, transducers were assigned to rod-drive level combinations in a balanced fashion (each transducer used in the same number of tests within a rod type), but each experimental matrix is unbalanced. A completely balanced experimental matrix would have $(t \times r \times d)$ elements corresponding to t transducers, r rods and d drive levels. The matrices used in this study are $(1 \times r \times d)$ -dimensional.

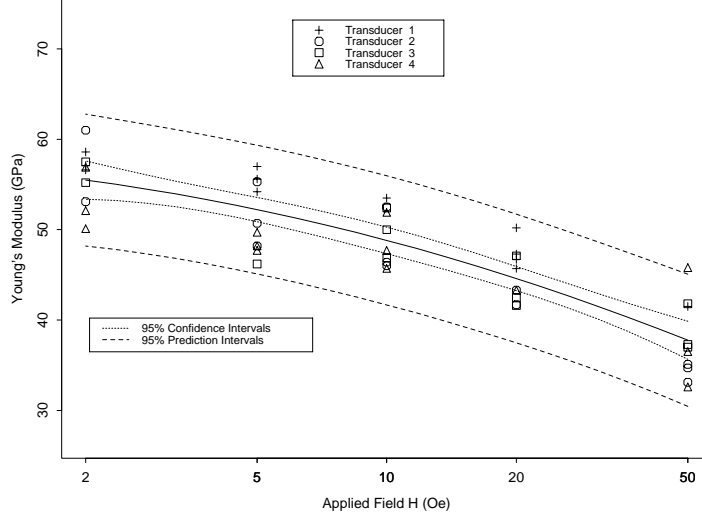


Figure 1: Baseline study: Young's modulus at constant applied field, E_y^H . Rod type D experimental data, estimated means (solid line), and 95% confidence and prediction intervals.

The mean response is also included in Figure 1, together with 95% confidence and prediction intervals computed from the standard error of the least squares fit. There is 95% confidence that the average Young's modulus of type-D material will lie within the region delimited by the confidence interval lines. Similarly, 95 out of 100 times the Young's modulus of any individual type-D rod will lie within the region delimited by the two prediction interval lines.

Figure 2 shows the Young's modulus experimental data and fitted curves for rod types A, B, C and E. On comparison with published data (Ref. [11], for instance), it seems feasible that decreasing trends are to be expected in the applied field levels under study. Note, however, that due to the sensitivity of E_y^H to system parameters these functional relations may not hold under a different set of operating conditions.

The predicted mean responses are compared for all rod types in Figure 3. A decreasing, quadratic relationship is observed in all cases. High quasi-static strain samples (type-C material) show consistently the highest values of mean Young's modulus throughout the whole applied field range.

Figure 4 shows experimental data and fitted curves for axial strain coefficient, magnetomechanical coupling factor, and permeability at constant strain. In order to provide an assessment of the spread in the measurements at each drive level, the MSE (mean square of the error in the regression model) is compared among material types for each property in Table 2. The MSE is an estimator of the variance (σ^2), thus a small MSE indicates small spreads in the measurements whereas a large MSE suggests large spreads in the measurements. The coefficient of determination, R^2 , is often used to judge the adequacy of a regression model [12] and is also included in Table 2. The degrees of freedom left for error are provided as well.

Table 2: Baseline study: mean square of error (MSE), coefficient of determination (R^2), and degrees of freedom of error (df) in the regression models. Asterisks indicate *weighted* least squares fits.

Rod Type	E_y^H			q			k			μ^c		
	MSE	$R^2(\%)$	df	MSE	$R^2(\%)$	df	MSE	$R^2(\%)$	df	MSE	$R^2(\%)$	df
A	19.598*	85.80*	47*	0.0148	44.68	48	0.0016	48.67	47	0.3484	48.65	48
B	9.61	79.25	47	0.341*	48.64*	48*	0.0011	55.92	47	2.8708*	47.43*	48*
C	18.22	71.21	47	0.362	23.26	48	0.010	64.49	47	0.7207	41.78	48
D	12.07	77.08	47	0.088	51.18	48	0.0019	46.19	47	0.9063	30.90	48
E	15.67	72.87	47	0.198	31.84	48	0.011	67.91	47	0.3644	56.70	48

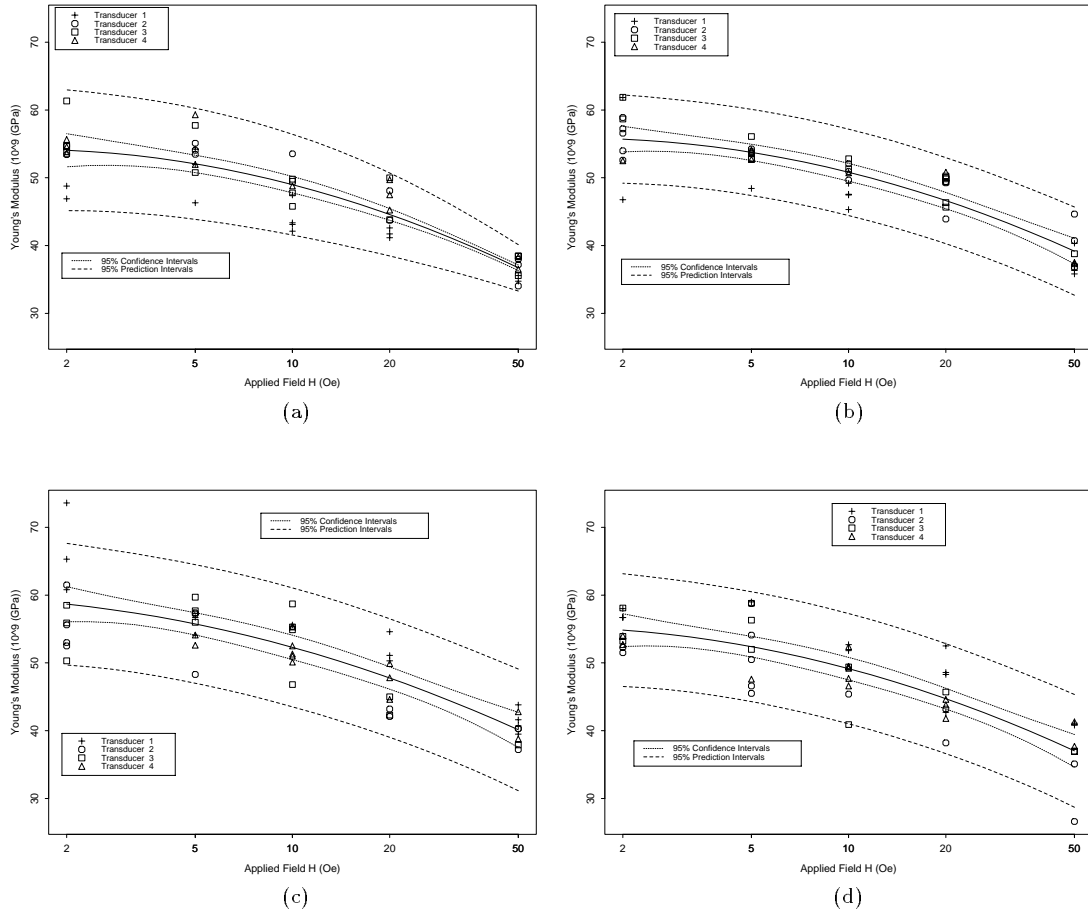


Figure 2: Baseline study: Young's modulus at constant applied field experimental data by transducer, estimated means, and 95% confidence and prediction intervals. Figures (a) through (d): rod types A, B, C, and E respectively.

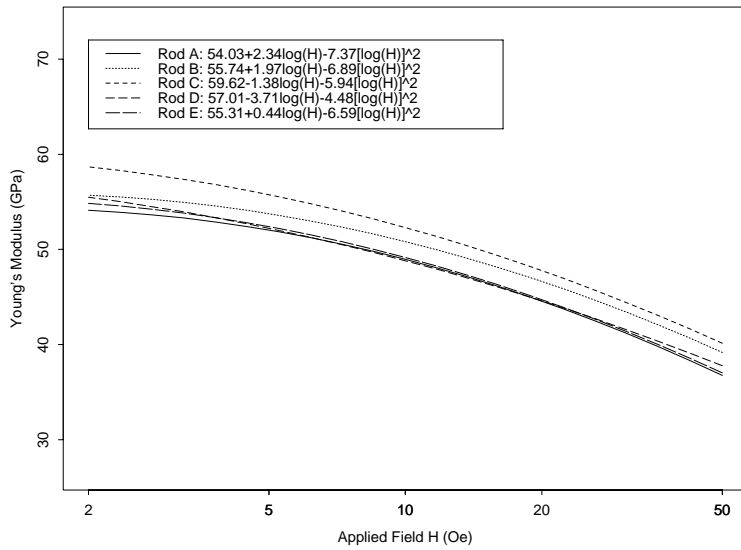


Figure 3: Baseline study: fitted mean curves of Young's modulus at constant applied field, E_y^H , by rod type.

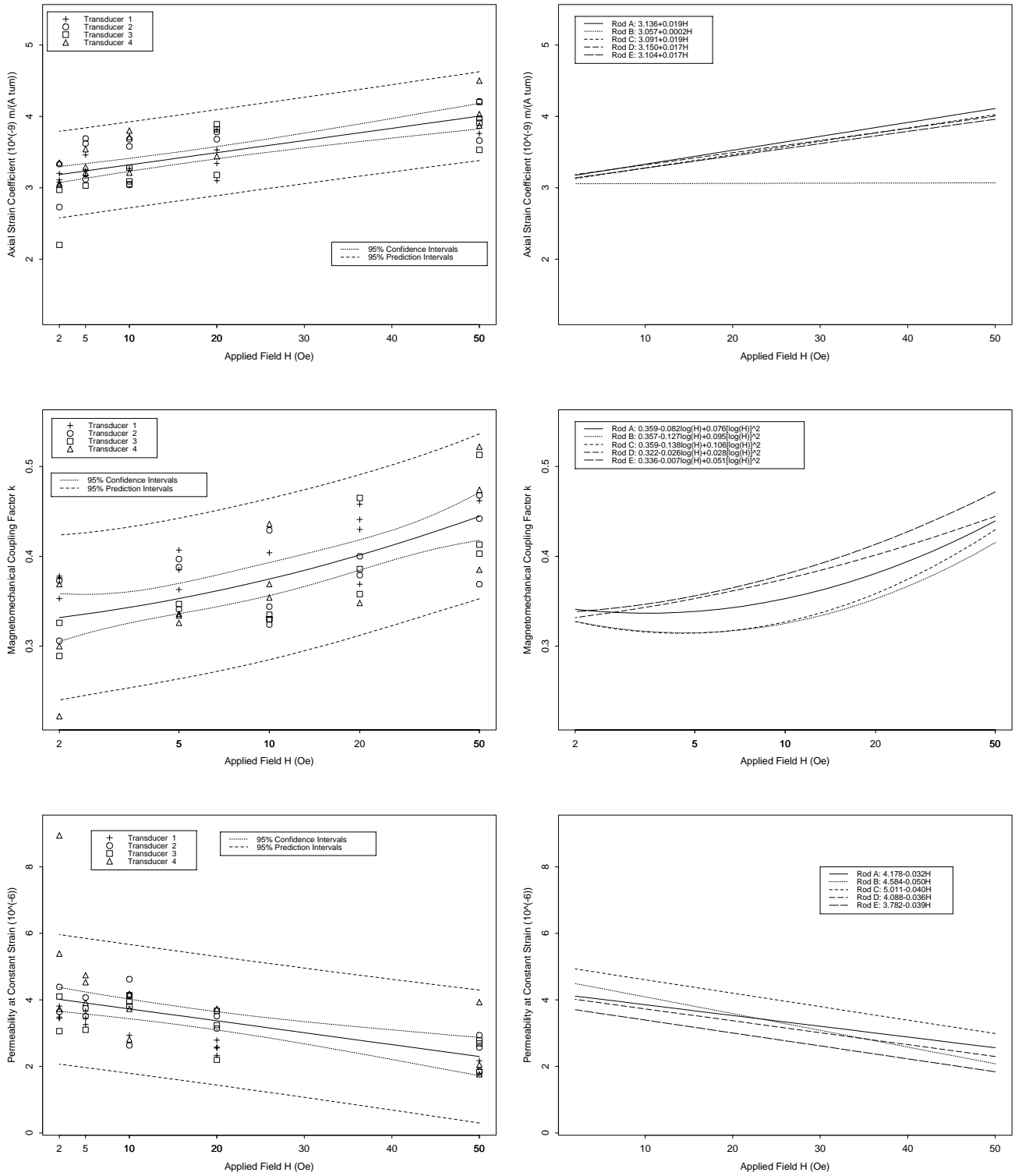


Figure 4: Baseline study. From top to bottom: axial strain coefficient, q , magnetomechanical coupling, k , and permeability at constant strain, μ^e . Left: type-D material experimental data, mean response, and 95% confidence and prediction intervals. Right: fitted means for rod types A through E.

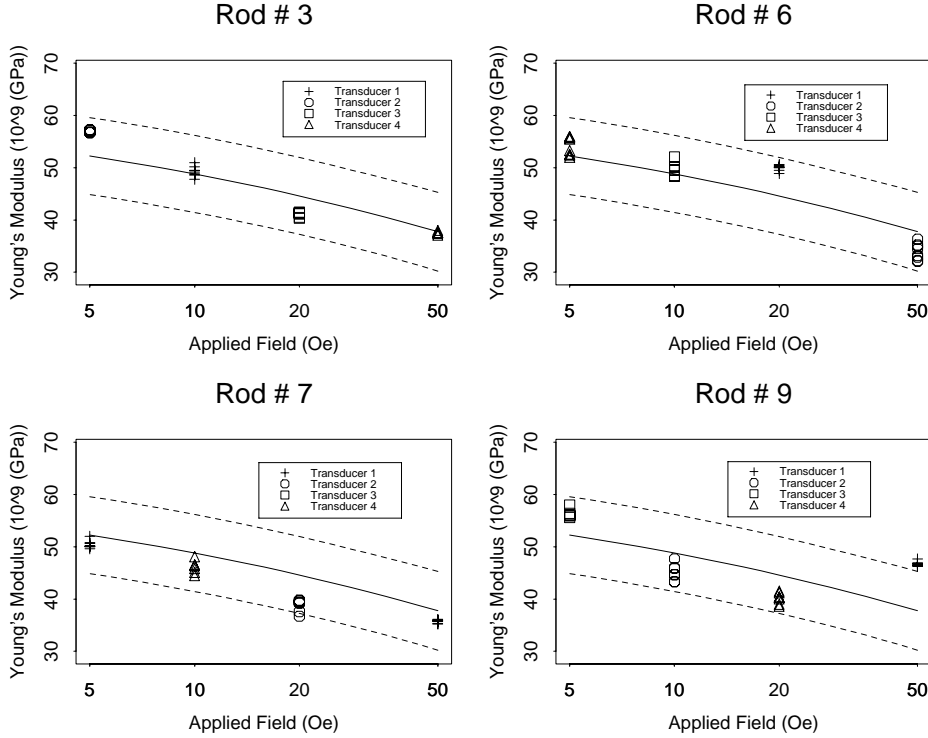


Figure 5: Repeatability study: rod type D Young’s modulus at constant applied field experimental data, sorted by rod. The solid and dashed lines represent estimated means and 95% prediction intervals, respectively, computed from the baseline data (see Fig. 1).

3.2 Repeatability study

Young’s modulus at constant field repeatability data of four rod type D samples are presented in Figure 5. Each lump of data-points represents 8 repeated tests in one of the four transducers indicated in the captions. Note that the scatters observed in the repeatability results do encompass the prediction intervals estimated from the baseline type-D material study.

One parameter that quantifies relative uniformity in a given set of repetitions is the coefficient of variation, which is defined as

$$c.v. = 100\% \times \frac{\sigma}{\mu}$$

where σ is the standard deviation and μ is the mean value of the measurements. The smaller the coefficient of variation, the more “repeatable” a measurement is said to be. The coefficients of variation range approximately

Table 3: Repeatability study: type-D material. Summary statistics for Young’s modulus at constant applied field, by rod and by drive level. Each set of repetitions was performed in transducer “Tr”.

Drive Level	Rod #3				Rod #6				Rod #7				Rod #9			
	\bar{x}	s	cv %	Tr	\bar{x}	s	cv %	Tr	\bar{x}	s	cv %	Tr	\bar{x}	s	cv %	Tr
5	56.938	0.250	0.44	2	54.175	1.753	3.24	4	50.425	0.732	1.45	1	56.250	0.741	1.32	3
10	49.288	0.988	2.00	1	49.725	1.174	2.36	3	46.129	1.159	2.51	4	45.025	1.474	3.27	2
20	41.112	0.455	1.11	3	50.000	0.558	1.12	1	38.888	1.117	2.87	2	40.163	0.984	2.45	1
50	37.563	0.245	0.65	4	33.925	1.542	4.55	2	35.725	0.320	0.90	1	46.725	0.462	0.99	4
Average	46.225	0.561	1.05		46.956	1.313	2.82		41.679	0.758	1.93		47.041	0.971	2.01	

between 0.44-4.55% in this particular case. Table 3 summarizes the calculations of means (\bar{x}), standard deviations (s), and coefficients of variation (cv) for the rod type D data at each applied magnetic field level. Average coefficients of variation of individual samples range between 1-2.8%, as shown in the last row of the table. The average coefficient

of variation of the four rods (overall mean cv of the lot) is used for comparison between rod types.² For this particular rod type, the average coefficient of variation of the lot is $cv=1.95\%$. Table 4 compares coefficients of variation for all rod types, sorted by property.

Table 4: Repeatability study: average coefficients of variation (%) by rod type and by property. Asterisks indicate data affected by a faulty accelerometer.

Rod Type	Property			
	E_y^H	q	k	μ^ϵ
A	1.75	4.57*	3.48	11.69*
B	0.74	0.96	1.92	5.15
C	0.72	2.14	1.82	4.88
D	1.95	2.13	1.99	5.72
E	1.71	1.91	1.79	5.66

Rod type A material properties have consistently larger sampling errors for all properties. The authors believe higher coefficients of variation were observed in this rod type due to two unaccounted for factors: 1) possible operator-related experimental errors in the early stages of this 12-month study (a “learning curve” factor), and 2) the results are thought to be biased due to a faulty accelerometer which exhibited intermittent low frequency noise (this affects only q and μ^ϵ .) A different accelerometer was used in rod types B-E tests.

Despite these two factors affecting the A-type material data, the results reveal that no fundamental differences are evident among rod types, either among all five rod types considered individually or between solid and three-laminate material. The coefficients of variation are, in most cases, smaller than $\approx 5\%$.

Comparing coefficients of variation among properties, the Young’s modulus seems to exhibit more robustness than the other three material properties under study. On the other hand, the permeability at constant strain exhibits the highest coefficients of variation. This is not altogether unexpected, because unlike the other properties three different sets of measurements (acceleration, input voltage, and input current functions) were used in calculating μ^ϵ from the test data. It is likely that error from the three measurements combined (in a propagation of error fashion) to yield increased μ^ϵ sampling errors, and hence higher coefficients of variation.

3.3 Mass load sensitivity study.

A modified statistical model is assumed in which a given combination of transducer, drive level and Terfenol-D sample is treated as a block within which each of the three loading cases described in Section 2.4 is applied once. The following model is assumed,

$$Y_{ijk} = \mu + \rho_i + \beta_{ij} + \lambda_k + (\rho\lambda)_{ik} + \epsilon_{ijk}$$

where: Y_{ijk} is the observation under the i th rod type, j th block (transducer-drive level-rod combination) and k th loading case; ρ_i is the main effect of the i th rod type; β_{ij} is the main effect of the j th block nested in the i th rod type; λ_k is the main effect of the k th loading case; $(\rho\lambda)_{ik}$ is the interaction between the i th rod type and the k th loading case; and ϵ_{ijk} is the random term due to experimental error. Significant factors and interactions are identified from ANOVA calculations and F-tests based on Type III sums of squares (see footnote on page 4). Nominal differences among loading cases estimated means are investigated by computing 95% Bonferroni intervals [13].

Mean curves were fitted using the model above. The mean curves corresponding to E_y^H are illustrated in the conditioning plot in Figure 6, which also shows experimental data and confidence intervals. Two issues regarding the four-times-the-mass loading case (4x) merit discussion here: 1) the experimental data points lie well within the prediction intervals computed in the baseline study, and 2) the fitted curves do not agree with the trends observed

²Note that the average coefficient of variation for each rod (average cv) is not equal to the pooled standard deviation (average s) divided by the mean (average \bar{x}). The average of the coefficients of variation gives, in this case, a better estimation of the expected repeatability.

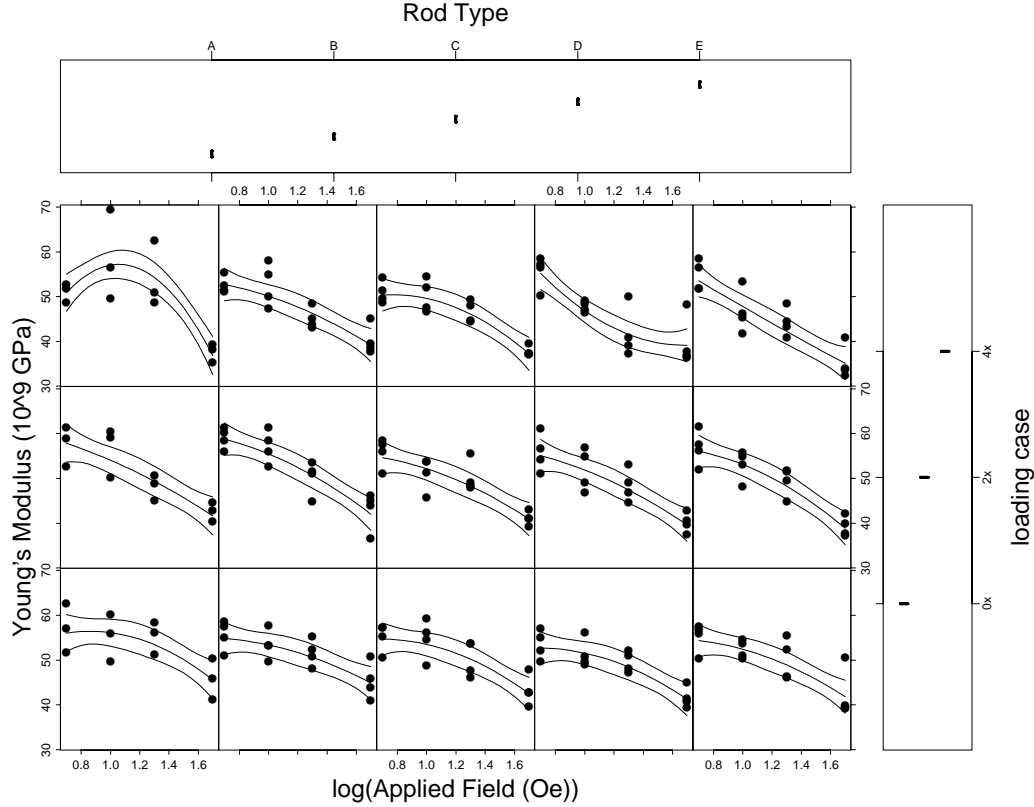


Figure 6: Mass load sensitivity study: conditioning plot of Young's modulus at constant applied field, E_y^H , by rod type.

in the baseline study (Figures 1 and 2). The latter observation demonstrates the pitfalls of modeling Terfenol-D material property trends with limited sample sizes. The no-mass (0x) and two-times-the-mass (2x) loading cases trends appear to agree with the results observed in the baseline study in terms of the *shapes* observed in the fitted curves. However, conclusive results cannot be addressed at this stage, and extreme care must be exerted when using these functional relations for Terfenol-D transducer design.

A preliminary comparison between the different loading cases is intended. To accomplish this, it was decided to utilize the baseline data (tested with a 60 gram mass, sample size = 50) instead of the 4x data collected in the mass load sensitivity study (sample size = 16). Such comparison still provides useful preliminary insight on trends and may constitute solid grounds for future investigations. Figure 7 shows type-D material data for the four properties under study. These trends appear to show good consistency from material type to material type. Note the discrepancies between the baseline data and the 4x data, in particular the contradicting curvatures in the fitted mean responses of the Young's modulus at constant applied field.

4. CONCLUSIONS

The importance of gathering fundamental Terfenol-D material property information in a transducer environment was discussed. Functional expressions of four Terfenol-D material properties (E_y^H , q , k , and μ^ϵ) as a function of applied magnetic fields up to 50 Oe were developed. By using statistics principles, 95 % prediction and confidence intervals were calculated. These intervals provided formal assessment of the experimental error under varied applied fields and controlled transducer parameters.

The ability to reproduce measurements in Terfenol-D transducers was studied. Results obtained by assessment

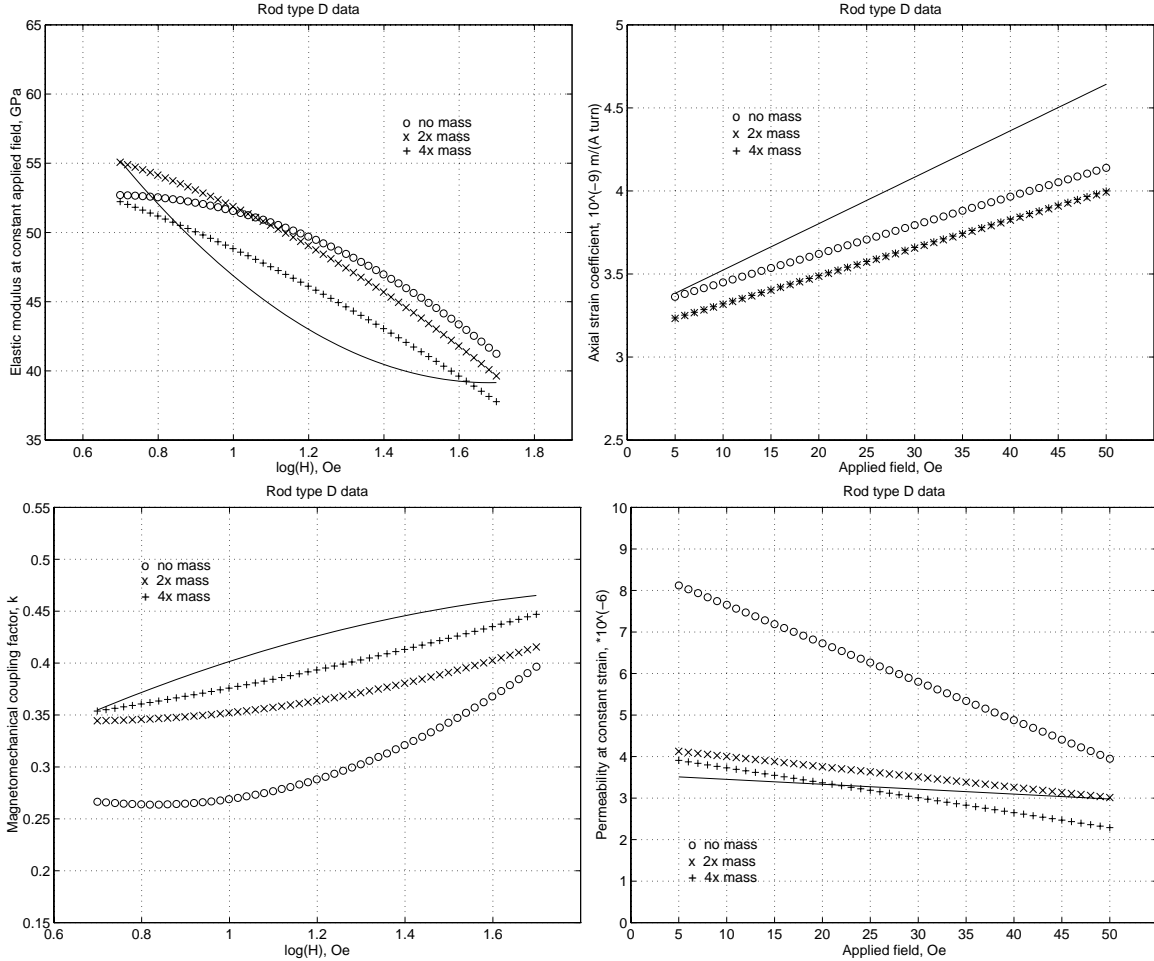


Figure 7: Mass load sensitivity study: comparison of fitted means between 0x, 2x, and 4x mass loading cases. Solid lines correspond to the 4x mass load sensitivity data (sample size = 16); the '+' lines correspond to baseline data (sample size = 50). Clockwise: Young's modulus at constant applied field, axial strain coefficient, magnetic-to-mechanical coupling, and permeability at constant strain.

of coefficients of variation to repeated measurements under fixed drive levels and controlled transducer conditions demonstrated that, in most cases, the measured coefficients of variation were smaller than $\approx 5\%$.

Finally, the sensitivity of Terfenol-D transducers to load changes was investigated. This study inadvertently emphasized the importance of adequate sampling in Terfenol-D transducer studies, and provided preliminary insight on variation of material properties under varied loads. Ongoing research work will provide additional information on this matter.

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