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LeAnn E. Faidley
Ohio State University

Marcelo J. Dapino
Ohio State University

Gregory N. Washington
Ohio State University

Thomas A. Lograsso
Iowa State University, lograsso@ameslab.gov

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Abstract

Recent work on ferromagnetic shape memory nickel-manganese-gallium (Ni-Mn-Ga) has demonstrated several characteristics which make this material attractive as an active element for the next generation of intelligent transducers. Alloys of martensitic Ni-Mn-Ga can strain up to 6% as a result of the rotation of twin variants and associated twin boundary motion which occur in these materials in response to magnetic fields. The magnetic actuation holds promise in transducer design because it can lead to enhanced frequency response compared with shape memory alloys with comparable strains. In this paper, we report on experimental measurements collected from a Ni50 Mn28.7 Ga21.3 sample which has been tested in a solenoid transducer by means of a novel drive configuration consisting of a collinear uniaxial field-uniaxial stress pair. We have observed that the elastic modulus of a Ni-Mn-Ga sample driven in these conditions changes substantially in response to varying bias field. In this paper, we further investigate the dependence of the elastic modulus on ac field intensity and mechanical load as well as bias field. Quasistatic, white noise, and swept-sine excitations were employed to examine the behavior of Ni50 Mn28.7 Ga21.3 driven under various combinations of magnetic fields and mechanical loads. Mechanically free quasi-static tests demonstrate reversible strains of 6300 με which are consistent with prior measurements on samples with similar composition near the Heusler stoichiometry. Dynamic measurements reveal a significant stiffness increase, of up to 209%, with dc bias field. This frequency shift or ΔE effect is shown to originate in the Ni-Mn-Ga sample and is believed to stem from the reorientation of twin variants in response to varying dc field. These results might facilitate a new class of solenoid-based Ni-Mn-Ga transducers for tunable vibration absorber applications, and lay the ground work for developing methods and criteria for the implementation of broadband Ni-Mn-Ga transducer technologies.

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DYNAMIC RESPONSE IN THE LOW-KHZ RANGE AND DELTA-E EFFECT IN FERROMAGNETIC SHAPE MEMORY NI-MN-GA

LeAnn E. Faidley
Marcelo J. Dapino *
Gregory N. Washington
Department of Mechanical Engineering
The Ohio State University
Columbus, Ohio, 43210

Thomas A. Lograsso
Ames laboratory
U.S. Department of Energy
Iowa State University
Ames, Iowa, 50011

ABSTRACT

Recent work on ferromagnetic shape memory nickel-manganese-gallium (Ni-Mn-Ga) has demonstrated several characteristics which make this material attractive as an active element for the next generation of intelligent transducers. Alloys of martensitic Ni-Mn-Ga can strain up to 6% as a result of the rotation of twin variants and associated twin boundary motion which occur in these materials in response to magnetic fields. The magnetic actuation holds promise in transducer design because it can lead to enhanced frequency response compared with shape memory alloys with comparable strains. In this paper, we report on experimental measurements collected from a $Ni_{50}Mn_{28.7}Ga_{21.3}$ sample which has been tested in a solenoid transducer by means of a novel drive configuration consisting of a collinear uniaxial field- uniaxial stress pair. We have observed that the elastic modulus of a Ni-Mn-Ga sample driven in these conditions changes substantially in response to varying bias field. In this paper, we further investigate the dependence of the elastic modulus on ac field intensity and mechanical load as well as bias field. Quasi-static, white noise, and swept-sine excitations were employed to examine the behavior of $Ni_{50}Mn_{28.7}Ga_{21.3}$ driven under various combinations of magnetic fields and mechanical loads. Mechanically free quasi-static tests demonstrate reversible strains of 6300 $\mu\varepsilon$ which are consistent with prior measurements on samples with similar composition near the Heusler stoichiometry. Dynamic measurements reveal a significant stiffness increase, of up to 209%, with dc bias field. This frequency shift or ΔE effect is shown to originate in the Ni-Mn-Ga sample and is believed to stem from the reorientation of twin variants in response to varying dc field. These results might facilitate a new class of solenoid-based Ni-Mn-Ga transducers for tunable vibration absorber applications, and lay the ground work for developing methods and criteria for the implementation of broadband Ni-Mn-Ga transducer technologies.

INTRODUCTION

Ferromagnetic shape memory alloys (FSMAs) in the Ni-Mn-Ga system have been shown to produce large strains up to 6% when exposed to magnetic fields [1]. These strains result from the reorientation of twinned martensitic variants and associated twin boundary motion which occur as the easy crystallographic axis aligns with external magnetic fields. While these strains are on the same order of those seen in shape memory alloys (SMAs), the rotation of twin martensitic variants in response to magnetic activation is faster and thus can lead to faster response than those achieved through martensite-austenite phase transformations [2]. Upon removal of the external magnetic field, however, there is no restoring force to drive the twin boundary in the opposite direction and the field-induced strain is not recoverable.

To achieve large reversible field-induced strains, a compressive stress is typically applied perpendicular to the field direction that favors variants with the c-axis aligned along the compres-

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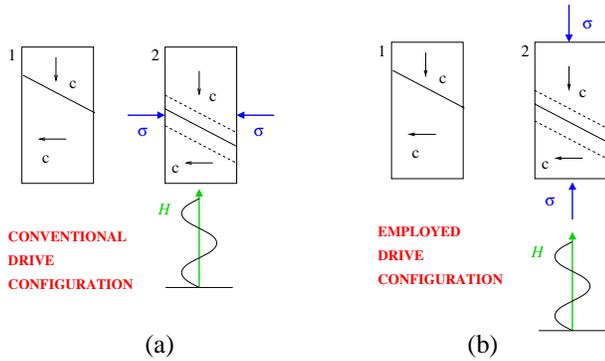*Address all correspondence to this author (dapino.1@osu.edu).

Figure 1. (a) Conventional perpendicular configuration for field-induced martensitic twin boundary motion; (b) collinear field-stress drive configuration employed in this paper.

sion axis. This *perpendicular* drive configuration is illustrated in Figure 1(a). In this investigation, experiments were conducted with the stress and magnetic field applied *collinearly* along the magnetic easy axis direction of the sample, contrary to the typical perpendicular arrangement (see Figure 1(b)). Despite the lack of a readily recognizable restoring mechanism, reversible strains as large as 6300 $\mu\epsilon$ (0.63 %) are demonstrated, which represent almost a four-fold improvement over the technologically more mature giant magnetostrictive material Terfenol-D. These reversible field-induced strains are seemingly too large to result from Joule magnetostriction nor can they be explained by the existing martensite variant reorientation models. In addition, contrary to the conventional processing practice of material "training" through field cycling and thermal treatments, these large strains were obtained from material tested as cast. The significance of the collinear stress-field configuration lies in that the magnetic field can be applied by a solenoid wrapped around a cylindrical rod, as opposed to a transverse electromagnet as is required for the perpendicular stress-field arrangement. Primary benefits of solenoid actuation over electromagnets include significantly smaller volume and weight. In addition, avoiding the use of electromagnets eliminate much of the demagnetization effects and eddy current losses which limit the frequency response of the Ni-Mn-Ga. For example, the solenoid based transducer to be described in the following section has shown response up to 5 kHz. Furthermore, we have shown that the collinear stress-field drive configuration can lead to significantly higher material stiffness than that previously measured employing conventional electromagnet tests [3].

The sample employed in this investigation has an average composition of $Ni_{50}Mn_{28.7}Ga_{21.3}$, that is lower in Mn and higher in Ga than the composition which exhibits 6% strains [4]. Despite the fractional increase in Mn content of the alloys studied in this and our prior investigations [3,5] with respect to those exhibiting the largest magnetic field-induced strains, significant and

profound differences are apparent in several regards, especially since the material investigated elsewhere is largely inactive when driven under collinear field-stress conditions. One difference lies in that the room temperature structure of the martensite phase at higher Mn content is orthorhombic rather than tetragonal [6]. A second and perhaps more significant difference is that for the sample tested, the shape memory martensitic transformation temperature is nearly coincident with the ferromagnetic ordering temperature, suggesting a coupled magneto-structural transformation which may be responsible for the observed reversible strains. Coupled transitions, known to exist in rare-earth-silicon-germanium compounds [7, 8], result in extraordinary magnetic responses including large magnetostriction, where the application of a magnetic field drives the structural change from a paramagnetic austenite phase to a ferromagnetic martensitic phase. This structural change is fully reversible when the magnetic field is removed.

The overall goal of this investigation is the determination of methods and criteria for the implementation of solenoid-based Ni-Mn-Ga transducers in dynamic environments. However, Ni-Mn-Ga compounds capable of large magnetically-activated responses under collinear field-stress conditions have been elusive, in part because the variant reorientation theories required for modeling and analysis of such compounds suggest that reversible strains stem exclusively from perpendicular field-field or field-stress configurations. Building on our prior results, and in order to ascertain the feasibility of collinear field-stress configurations compatible with solenoid-based transducers, this paper presents a quasi-static and dynamic characterization of the alloy $Ni_{50}Mn_{28.7}Ga_{21.3}$. Quasi-static measurements conducted under 0.5 Hz sinusoidal excitations reveal a maximum field-activated strain of 6300 $\mu\epsilon$. White noise and swept-sine excitations up to 5 kHz are employed to demonstrate large stiffness changes with varying bias fields and mechanical loads.

EXPERIMENTS

The experiments are focused on the quasi-static and dynamic characterization of a single crystal alloy with composition $Ni_{50}Mn_{28.7}Ga_{21.3}$ which was prepared by the Bridgman method. The single crystal ingot was oriented along the [100] direction and a 0.248 in (0.630 cm) diameter, 0.883 in (2.243 cm) long rod was cut from the ingot using electrical discharge machining (EDM). The experiments were conducted with a collinear magnetic field-stress pair in the broadband research transducer shown in Figure 2, which consists of a water-cooled solenoid, pickup coil, and magnetic steel components integrated to form a closed magnetic circuit. The solenoid consists of 1350 turns of AWG 15 magnet wire and has a field rating of 167 Gauss/A up to 8.1 kGauss. Interspersed within the solenoid lies a coil of 0.25 in diameter copper tubing which provides temperature control within ± 1 F by means of water flow at a rate of up to 6.35 L/min. The
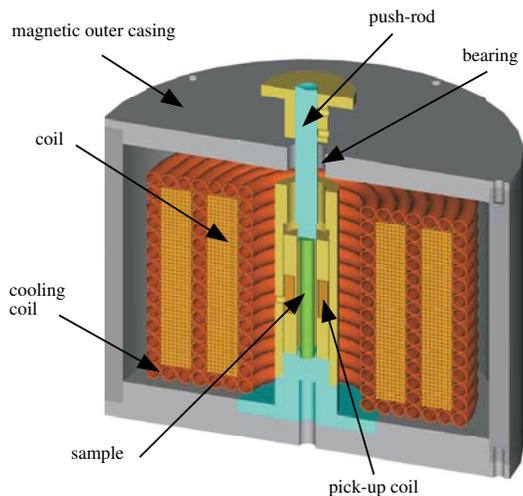
Figure 2. Cross-section of the broadband transducer employed in this study.

fact that the Ni-Mn-Ga is surrounded by a closed magnetic circuit ensures that demagnetization factors are negligible.

The solenoid is driven by two Techron 7790 4 kW amplifiers arranged in series with an overall voltage gain of 60 and a maximum output current of 56 A at the nominal solenoid resistance of 3.7 Ω. The magnetic induction is measured with a pickup coil made from AWG 33 insulated copper wire wound in two layers around an aluminum spool. The quasi-static strain is measured by means of a Lucas Shaevitz MHR-025 linear variable differential transducer (LVDT) while the dynamic response is measured by means of PCB U352C22 and 352C68 accelerometers. Several Omega thermocouples are used to monitor the system temperature through a 10-channel Omega signal conditioner. For loaded tests, several static loads ranging from 0 – 750 grams are used. The system is controlled by a a SigLab 20-42 data acquisition system interfaced through a PC. The test setup is illustrated in Figure 3.

The dynamic response of the Ni-Mn-Ga sample was studied by way of a combination of white noise excitation and swept-sine tests. The white noise excitation tests were conducted to determine frequency ranges where transducer and sample resonance behaviors occur, whereas the swept-sine excitation tests were employed to gather higher resolution data around the sample resonance frequency under various operating conditions. For both types of excitation measured responses include transfer functions pushrod acceleration per current, acceleration of transducer housing ("canister") per current, and electrical impedance computed from the pick-up coil voltage per input current. Three sets of swept-sine data were gathered in order to examine the effect of load, dc bias field, and ac field amplitude. In the first data

set, the mechanical load applied to the sample was varied from 0–750 grams for a bias level of 1.1 kOe (86.2 kA/m). A second set of tests were employed to determine the resonance over a range of bias fields from 0 – 1.6 kOe (0 – 129 kA/m). The tests were run in current controlled mode such that the applied ac field remained constant at 82.7 Oe (6.58 kA/m) which represents the largest field that the amplifiers can supply to the 13.5 mH inductive load at 5 kHz. In the final set of swept-sine tests, the ac field intensity was varied between 33.4 – 82.7 Oe (2.66 – 6.58 kA/m) while maintaining a constant 812 Oe (64.7 kA/m) bias field. Throughout all the tests, temperatures were monitored at the core of the solenoid as well as at the inlet and outlet of the cooling tubes to ensure constant temperature testing to within $\pm$ F. In addition, sufficient time was allowed between tests to ensure ambient temperature initial conditions on the Ni-Mn-Ga sample as well as to minimize thermal effects in the drive amplifiers.

EXPERIMENTAL RESULTS AND DISCUSSION
Quasi-Static Testing

Quasi-static testing was performed on the $Ni_{50}Mn_{28.7}Ga_{21.3}$ sample in the transducer shown in Figure 2 in order to determine the level of activity of this sample relative to other Ni-Mn-Ga compounds and other active materials. Mechanically-free measurements were conducted at 0.5 Hz under a sinusoidal magnetic field of amplitude 9.2 kOe (732 kA/m). Strain and magnetization results are shown in Figure 4, where corrections have been made to account for the magnetostriction of the transducer's steel end extensions and pushrod. The maximum strain of 6300 $\mu\varepsilon$ represents an increase of 47 percent over the maximum strain reported previously under collinear field-stress drive conditions [5]. It also represents a four-fold improvement over the saturation magnetostriction of Terfenol-D (1600 $\mu\varepsilon$).
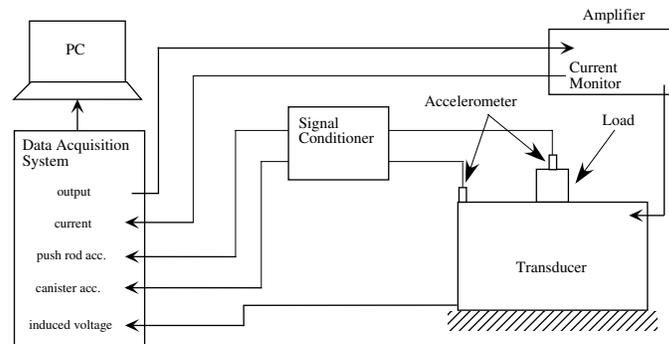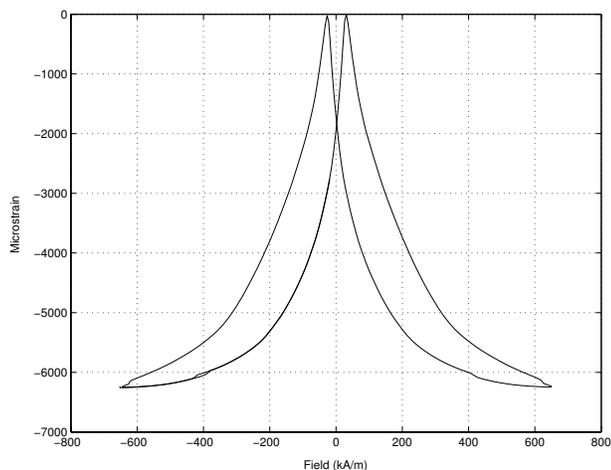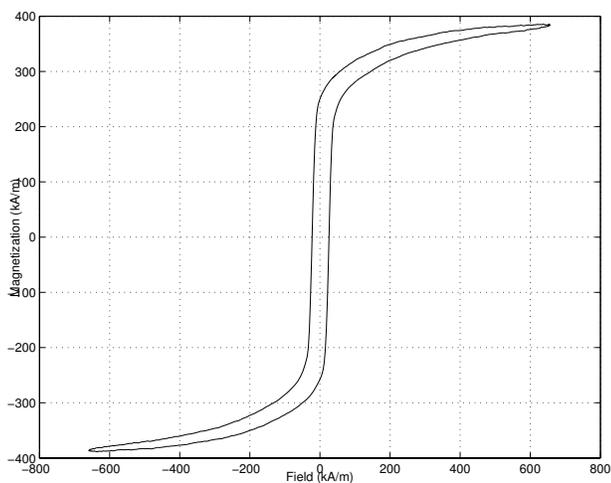

Figure 3. Experimental setup used for quasi-static and dynamic testing of Ni-Mn-Ga.

Figure 4. (a) Strain vs. field and (b) magnetization vs. field for $Ni_{50}Mn_{28.7}Ga_{21.3}$ at 0.5 Hz.

Dynamic Testing

The overall system response was measured using 0–20 kHz white noise excitation under a magnetic bias of 1.4 kOe (107.7 kA/m). The effective bandwidth of the solenoid transducer is eddy current-limited and estimated to be greater than 5 kHz. It is shown that the Ni-Mn-Ga response occurs below 5 kHz. In order to separate the transducer spectral components from those associated with the active sample, tests were conducted utilizing different core materials: Ni-Mn-Ga, 1018 steel, aluminum, and copper. Figure 5 shows the transfer function pushrod acceleration per current in these different cases. Notably, the location of the primary peak does not change with core material though their magnitudes change slightly due to slight variation in the system's mass and impedance. This indicates that, as expected,

the first axial resonance for the steel, aluminum, and copper are outside of the 20 kHz range. For example, the peak at 1.8 kHz is unaffected by the choice of material, thus suggesting it originates from transducer structural elements which are uncoupled from the core material.

Figure 6 shows the white noise response of the $Ni_{50}Mn_{28.7}Ga_{21.3}$ sample under various loads. The graph shows all of the same transducer peaks as those seen in Figure 5 but also exhibits new peaks at about 1.5 kHz for a 60 gram load and at about 0.5 kHz for a load of 750 grams. This peak is believed to be the primary resonance of the sample and is the focus of the tests presented in the following sections. It is not
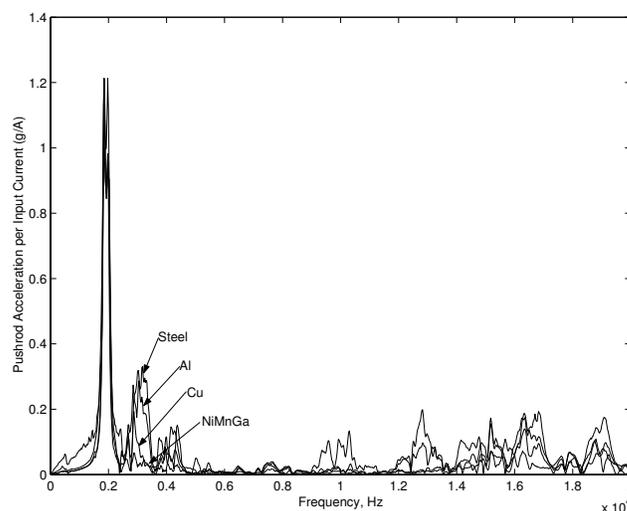

Figure 5. Transfer function pushrod acceleration per input current for white noise excitation for various core materials.
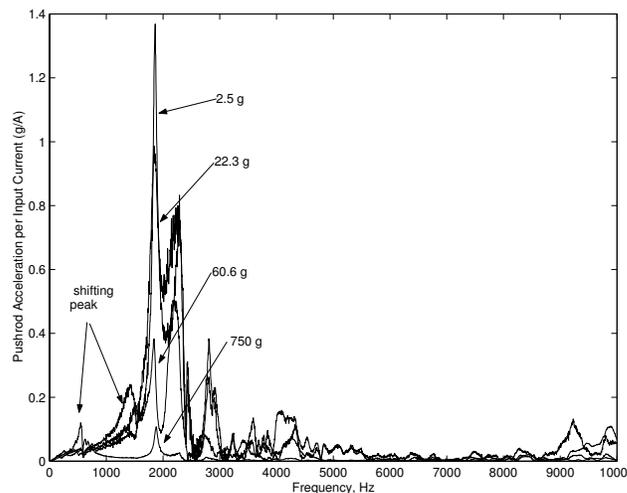

Figure 6. Transfer function pushrod acceleration per input current for white noise excitation at various loads.

visible for loads lower than 60 grams because for those loads it is located in regions dominated by transducer housing resonances. It is noted that as the load is increased, the amplitude of the peak at 1.8 kHz decreases substantially.

Effect of Load   The white noise excitation tests shown in Figures 5 and 6 suggest that there is a resonance peak located in the range below 1.8 kHz which stems for the Ni-Mn-Ga element and whose location is directly correlated to the externally applied mechanical load. Figure 7 shows the effect of mechanical load on the transfer function pushrod acceleration per current. For all of the curves, a fixed 1.1 kOe (86.2 kA/m) dc bias field and 82.7 Oe (6.6 kA/m) ac field amplitude were employed. Loads varying from 40.8 to 750 grams were applied since the resonance peaks for loads smaller than this lie within the activity region for the actuator structure and thus cannot be accurately measured. It is seen that as the load was increased the resonance shifted from about 1.4 kHz to about 0.5 kHz. Figure 8 shows the relationship between the applied mass, m, and the resonance frequency, f compared to the inverse squared relationship suggested by the simple 1 degree of freedom model

$$(2\pi f)^2 = \frac{k}{m} \tag{1}$$

where k is the stiffness of the series combination of Ni-Mn-Ga sample, end extensions, and pushrod, and m is the dynamic mass of the system which is the sum of the applied mass and one third of the sample, end extensions, and pushrod mass. The stiffness value, k, used for the model curve is the average of the stiffness values calculated for each peak from Equation 1. It is concluded that although there are slight deviations from the predicted trend due to the physical complexity of the transducer compared with the model, this model can provide adequate estimates of the overall material behavior.

Effect of Bias Field   Figures 9 and 10 show the results of swept-sine tests in which the bias levels were varied between 0–1.6 kOe (0–129.3 kA/m) for a 60.6 and 250.0 gram load. Part (a) of each figure shows the transfer function pushrod acceleration per input current, while part (b) shows the transducer housing acceleration per input current. The results suggest a substantial shift of the pushrod acceleration resonance peak which indicates a stiffening of the sample with increasing bias level. This trend is analogous to the resonance shift with bias field, or ΔE effect, observed in magnetostrictive materials. However, the effect observed here is not believed to stem from Joule magnetostriction, but from twin variant reorientation effects as suggested by quasi-static measurements. It is noted that the resonance peak showing the shift is not evident in the housing acceleration transfer
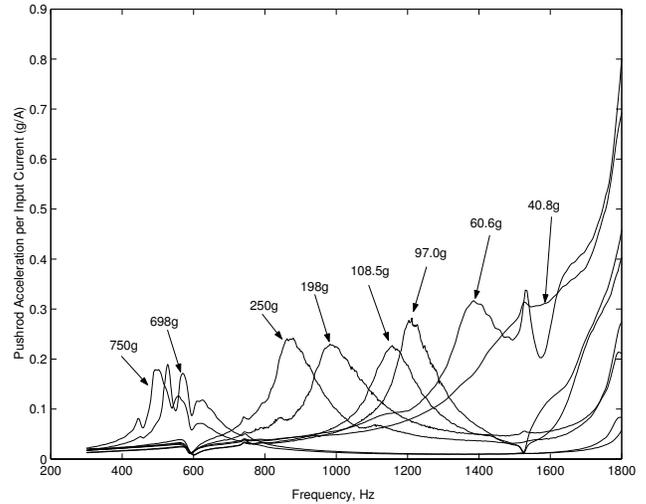

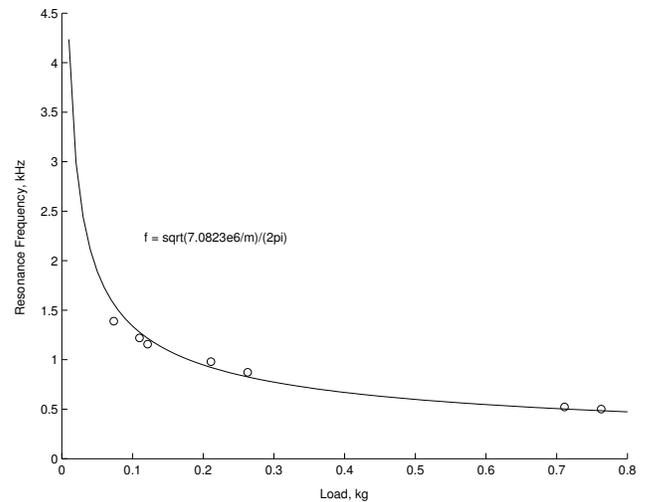Figure 7. Pushrod acceleration per input current for several applied loads for the Ni-Mn-Ga sample.

Figure 8. Comparison of experimental and 1DOF model results for frequency (f) as a function of load (m).

function, suggesting that this peak is in fact associated with the Ni-Mn-Ga sample rather than the transducer.

Figure 11 shows the transfer function pushrod acceleration per input current for the primary transducer resonance peak at 1.8 kHz. This peak also exhibits a shift with bias field showing a slight shift toward higher frequencies followed by a shift toward lower frequencies. A similar shift is seen in the equivalent transducer peak when an aluminum core is employed instead of Ni-Mn-Ga. This suggests that this shift is due to a change in stiffness of transducer components unrelated to the sample itself and also explains why this shift is substantially smaller that the shift seen in Figures 9 and 10. The results presented in [3] employed

the latter resonance shifts to calculate the ΔE effect in Ni-Mn-Ga since, under the unloaded conditions used, the existence of the sample resonance was not apparent. This resulted in the reporting of numbers much smaller than those presented below.

Effect of AC Drive Amplitude Figure 12 shows the effect of ac drive magnitude on the resonance frequency in the transfer function pushrod acceleration per input current for tests run with an 812 Oe (64.7 kA/m) magnetic bias and 60.6 gram load. In this case, the dependence of stiffness upon ac field intensity is quite weak.
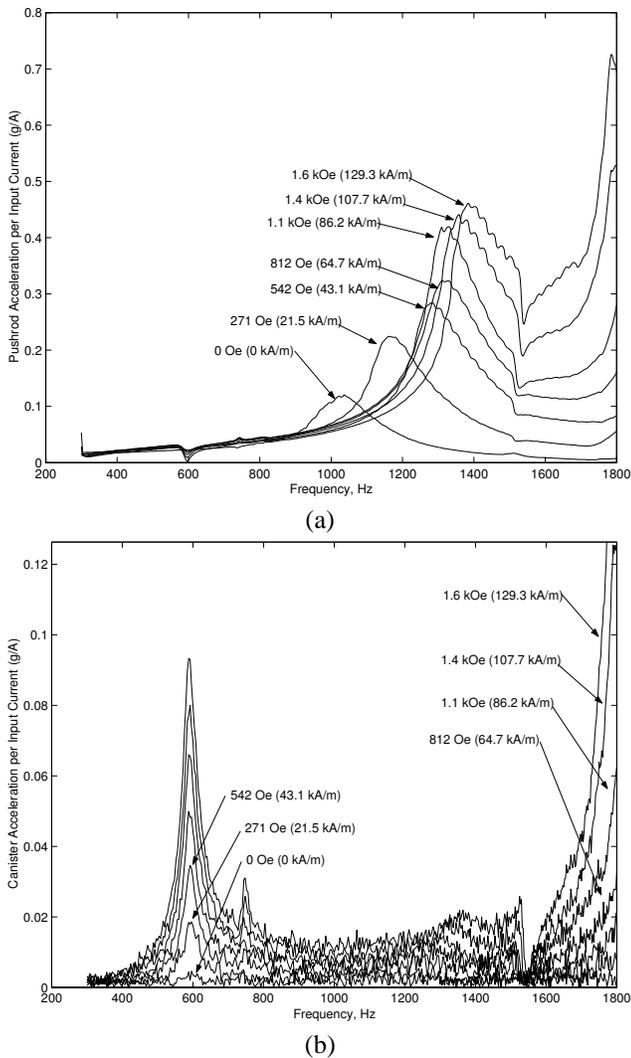

(a)

(b)

Figure 9. Transfer functions (a) pushrod acceleration per input current and (b) transducer housing acceleration per input current for the Ni-Mn-Ga sample loaded with 60 grams external load.
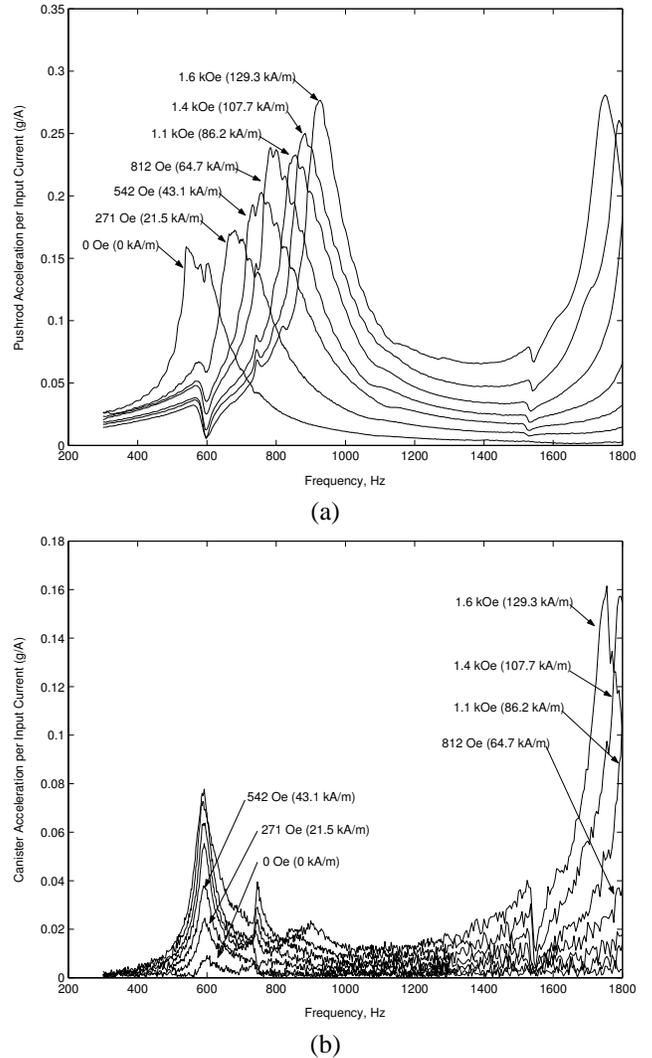

(a)

(b)

Figure 10. Transfer functions (a) pushrod acceleration per input current and (b) transducer housing acceleration per input current for the Ni-Mn-Ga sample loaded with 250 grams external load.

Delta-E Effect

The resonance shifts shown in Figures 9 and 10 represent a change in the stiffness or ΔE effect which stems from the response of Ni-Mn-Ga to applied fields. Figure 7 shows a shift in resonance due to applied mass. To quantify the stiffness shift, the following linear model for rod vibrations is employed,

$$k = \frac{AE}{l}, \qquad (2)$$

where A is the cross-sectional area, E is the elastic modulus of the sample, and l is the rod length. Combining relations (1) and (2)

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and observing that in these relations the stiffness k represents the series combination of the pushrod, end extensions, and Ni-Mn-Ga sample, allows for the determination of the elastic modulus of the material in each of the states represented in Figures 7, 9, and 10. The elastic modulus as a function of load is shown in Figure 13(a), while its dependence on bias field is shown in Figure 13(b).

Tables 1 and 2 show the numerical values for the points on the plots in Figure 13(a) and (b). According to the simple model (1) - (2) there is a 46% change in modulus with a change in load of about 700 grams. The overall trend shown is an increasing region followed by a slightly decreasing region as the load is
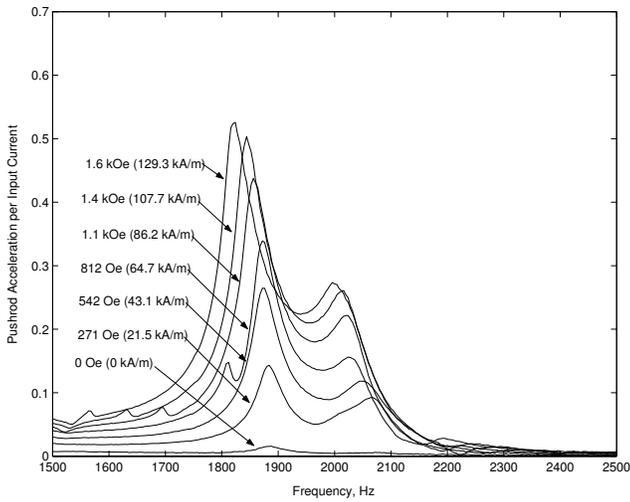

Figure 11. Pushrod acceleration per input current for the primary transducer resonance.
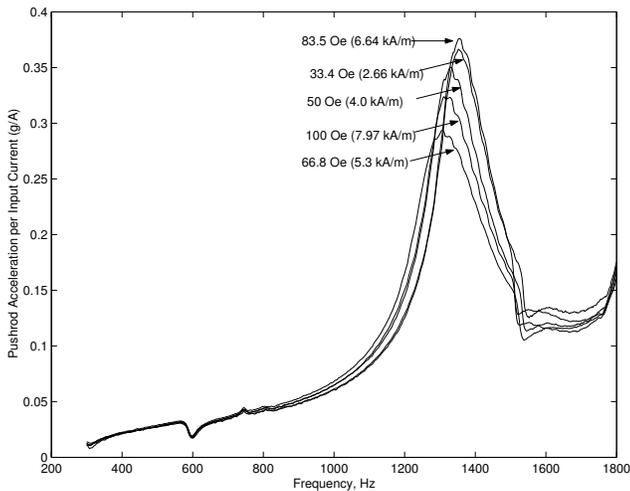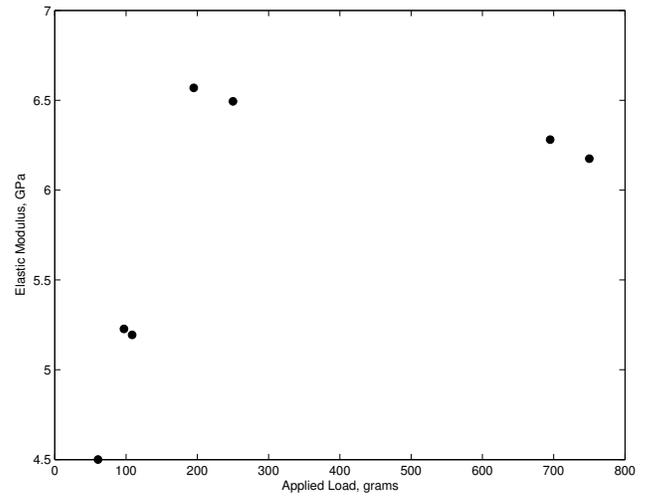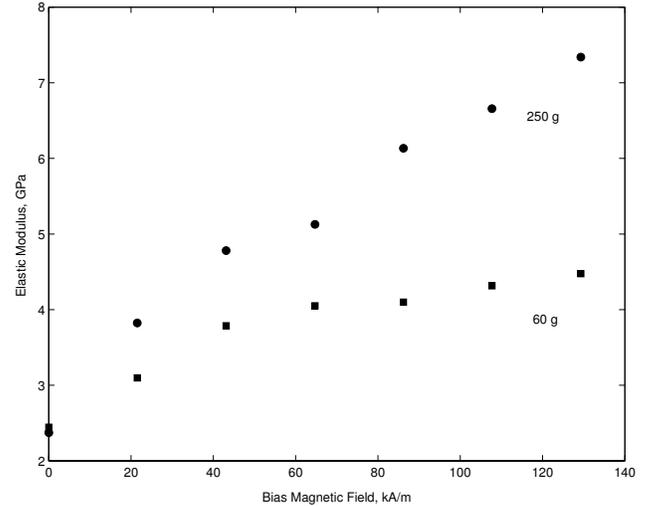

Figure 12. Pushrod acceleration per input current for several ac magnetic field levels.

(a)

(b)

Figure 13. Elastic modulus dependence on (a) applied load and (b) bias magnetic field.

Table 1. Elastic modulus dependence on applied load.

Load (grams)	Elastic Modulus (GPa)
60.6	4.500
97.0	5.228
108.5	5.194
198.0	6.569
250.0	6.494
698.0	6.281
750.0	6.175
$\Delta E \rightarrow$	46%

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Table 2. Elastic modulus dependence on bias magnetic field for 60 & 250 gram loads.

Magnetic Bias (Oe)	Elastic Modulus 60 gram load (GPa)	Elastic Modulus 250 gram load (GPa)
0 (0 kA/m)	2.445	2.372
100 (7.9 kA/m)	3.096	3.823
200 (15.9 kA/m)	3.787	4.780
500 (39.8 kA/m)	4.051	5.127
800 (63.6 kA/m)	4.099	6.134
1000 (79.6 kA/m)	4.315	6.580
1500 (119.4 kA/m)	4.476	7.339
$\Delta E \rightarrow$	83%	209%

increased. The dependence of elastic modulus on magnetic bias field is much more significant than that of load. Elastic modulus varies by 83% with magnetic bias field for the 60 gram load and by 209% for the 250 gram load. This ΔE effect is on the order of magnitude as that seen in Terfenol-D and also shows the same increasing trend [9].

CONCLUDING REMARKS

The quasi-static and dynamic behavior of $Ni_{50}Mn_{28.7}Ga_{21.3}$ under a collinear uniaxial stress - uniaxial magnetic field pair have been examined for various mechanical loads, bias magnetic fields, and ac field amplitudes. Quasi-static testing demonstrates that the mechanically-free Ni-Mn-Ga sample exhibits reversible strains of up to 6300 $\mu\varepsilon$ (0.63%). This result is consistent with prior results obtained from material of similar composition. Dynamic testing identified the sample resonance peak at about 0.5 kHz when the sample was loaded with 750 grams. This peak was found to shift upwards into the frequency range dominated by transducer resonance at about 1.8 kHz when the load was reduced to under about 50 grams. The peak also exhibited a significant shift toward high frequencies as the magnetic bias field was increased from 0 – 1.6 kOe (0 – 129.3 kA/m). This shift indicates a stiffening of the sample which corresponds to a ΔE effect of 83% for the 60 gram load and 209% for the 250 gram load. The magnitude of this field-induced ΔE effect suggests that this material will be valuable for applications such as tunable vibration absorbers. Future work will involve the complete mapping of this Ni-Mn-Ga composition with respect to bias field and mechanical load in order to verify the trends found here. In addition, models will be developed to predict this behavior and to help understand the overall behavior of Ni-Mn-Ga when activated by a collinear stress-field pair.

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