Broadband Performance of a Magnetostrictive Shaker

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ABSTRACT: Performance data from a magnetostrictive broadband (100 Hz-10 kHz) vibration source is presented. An original design for a magnetostrictive transducer was built and tested. The transducer used a rod of ETREMA Terfenol-D™ (EDGE Technologies, Ames, Iowa) as the motion source (rod dimensions: 51 mm long x 6.35 mm diameter). This communication will convey the characteristics of magnetostrictive transducer behavior. The shaker is considered to be a single input (electric current) single output (force) system. For low signal operation it behaves in a linear fashion; output force is proportional to input electric current and harmonic content is low. Comparisons with a commercially available permanent magnet shaker show that the magnetostrictive shaker's linear region extends to high enough forces (or displacements) to be of use as a vibration excitation source. Higher input currents eventually lead to degradation of the magnetostrictive shaker's linear behavior; output harmonics become appreciable, force levels increase disproportionately and, of course, linear systems analysis techniques become inappropriate. The magnetostrictive shaker discussed is capable of producing peak acceleration amplitudes in excess of 1960 m/s^2 (200 g's, at frequencies greater than 4 kHz with a 24 gram load using sinusoidal excitation). Experimental results are presented for: 1) output force as a function of frequency, load, and current amplitude (30 Hz-10 kHz with sinusoidal excitation); 2) typical electrical impedance as a function of frequency; 3) frequency response functions as Newtons per ampere, Newtons per volt, and meter per ampere; and, 4) performance comparisons made with a commercially available permanent magnet shaker. Experimental results 2,

3, and 4 are for operation of the magnetostrictive shaker in its linear range (linear in a least squares sense).

INTRODUCTION TO MAGNETOSTRICTIVE MATERIALS AND ACTUATORS

Magnetostrictive materials strain in response to magnetic fields. Terfenol-D is a magnetostrictive material composed of rare-earths, terbium and dysprosium, alloyed with iron (Ter = terbium, fe = iron, nol = Naval Ordinance Laboratory, where the material was first developed, and D = dysprosium). Terfenol-D's utility arises from its giant strains, 1000-2000 x 10^{-6} m/m, due to readily attainable magnetic field amplitudes, i.e., typically less than 1000 Oersted ≈ 79.6 x 10^{3} amp/meter.(Butler, 1988) Terfenol-D was the magnetostrictive material selected for use in the transducer design to be discussed.

When Terfenol-D is produced in rod form, its small "oblong" magnetic domains are intentionally oriented with the longer axis perpendicular to the rod's longitudinal axis. Application of a magnetic field along the longitudinal axis of the rod, in either direction, causes the magnetic domains to rotate so that their longer axis is parallel with the rod's. As this occurs, the rod gets longer (and smaller in diameter).

A few items of general interest about Terfenol-D warrant discussion. First, it tends to deliver larger net strains if it is compressively prestressed. When the material is manufactured in rod form this prestress acts to rotate more magnetic domains further away from an axial orientation. The net result is the possibility of increased strain with the application of a magnetic field. Second, its compressive and tensile strengths are approximately 700 and 28 MPa, respectively.(Butler, 1988) The material should not be drilled or threaded since it can only be described as "brittle." Third, Terfenol-D filings are flammable.

Fourth, and most significant from an actuator design standpoint, Terfenol-D strain as a function of applied magnetic field displays hysteresis, owing to magnetic hysteresis within the material. A sketch of this hysteresis is shown in Figure 1. Note, both positive and negative magnetic fields result in positive strain (the rod increases in length). To allow for bidirectional motion, a rod is typically magnetically biased to H_o (via an external permanent magnet or a DC current in the coil). The field from an electric current in a surrounding wire coil, or solenoid, can then be used to control the net magnetic field within the Terfenol-D rod. (Recall: $H \approx nI$, where n is the number of turns per unit length of the solenoid and "I" is the electrical current passed through the solenoid.)

An oscillating current in the solenoid causes the Terfenol-D rod length to oscillate. Unfortunately, from a linear systems point of view, while oscillating the material must traverse the hysteresis loop depicted in Figure 1. Harmonics present within the output acceleration frequency spectrum of Terfenol-D transducers are due in part to this hysteresis. The relative amplitudes of the resulting harmonics are primarily a function of how hard the transducer is being driven. More on this topic is included with the results discussion.

Traditional uses of Terfenol-D transducers include positioners (Miller, 1991) and sonar projectors (500 - 2000 Hz). Additional work has shown its applicability to use in isolators (5 - 60 Hz, (Hiller et al., 1989)) and mounts (single sine "shock" attenuation (Reed, 1988)). In a recent project, a Terfenol-D transducer was designed, built, and tested for use in a study of tissue response to internal vibrations.(Hall, 1991) That transducer was designed to mimic the vibrations of an artificial heart from 300 Hz to 10 kHz.

THE MAGNETOSTRICTIVE TRANSDUCER

Figure 2 is a section assembly drawing of the Terfenol-D magnetostrictive transducer used in this investigation. The external geometry of this design was chosen to suit its intended use as a general laboratory vibration source. It will also serve as a test fixture for measuring the performance of different Terfenol-D rods (h), springs (e), prestresses (via (i) and (e)), air gaps (between (c) and (a)), and H_o values (adjustable using the external solenoid, (g)).

A constant magnetic field is provided to the Terfenol-D rod by the cylindrical permanent magnet, (f), and by a DC current in the external wound wire solenoid, (g). An AC electric current provided to the internal solenoid results in an oscillating magnetic field along the longitudinal axis of the transducer. The external solenoid and permanent magnet's fields provide the offset H_o indicated in Figure 1, biasing the Terfenol-D to approximately one-half of its maximum strain. The field from the internal solenoid is used to add to, or subtract from, this "DC" field, the result is bidirectional motion of (a) relative to the housing. This is the basis for the transducer input-output relationship.

The path for the magnetic flux is (f)-(k)-(i)-(h)-(a)-(c)-(f). The housing components, (d) and (j), are made of aluminum since it is approximately magnetically "neutral" (and readily available). The components along the flux path are made of "high" permeability, fully annealed 1020 steel.

The transducer incorporates a simple prestress adjusting scheme. In addition, the design is such that the cylindrical air gap in the magnetic circuit (between (c) and (a)) remains constant (radial clearance of approximately 0.010") through the entire strain cycle of the rod.

EXPERIMENTAL DETAILS

A schematic for the experimental set-up is shown in Figure 3. The accelerometer (Kistler 808A) charge amplifier pair, the resistor (used for estimating current values), and the Tektronix 2630 Fourier Analyzer were calibrated before these measurements were performed. For the accelerometer, the charge sensitivity versus frequency was plotted and a linear least squares curve fit was performed. Broadband measurements from 0-10 kHz were scaled using the charge sensitivity implied by the curve fit evaluated at the center frequency of 5000 Hz. The maximum deviation from this value was eight percent. The standard deviation was 3.5%. Measurements taken at single frequencies were scaled by the appropriate charge sensitivity values from the calibration data. The amplifier shown in Figure 3 was simply a standard 50 Watt audio amplifier. One end of the shaker was attached to ground during tests by bolting it to the floor on hard rubber pads. Thus, relative motion between the ends of the shaker's magnetostrictive rod corresponded to absolute motion of the shaker's free end.

The influence of structural resonances introduced by the actuator mechanical design and the shaker mounting configuration during tests were assessed as follows. A modal analysis using an impact hammer identified a rigid body mode near 1500 Hz due to the shaker-floor mounting configuration. Also, several translational and rocking housing-rod modes were identified between 2500 and 3800 Hz, including well defined structural modes with the upper housing and rod motion out of phase near both 2700 Hz and 3600 Hz. The impact testing upper frequency was limited to about 5000 Hz, above which it was difficult to excite the aluminum housing without denting or deforming the housing material. Structural effects above 5 kHz were estimated by comparing axial accelerations of the upper and lower housings. The accelerometer attached to the upper housing indicated consistently high readings around 9000 Hz. A simple linear vibration model of the upper housing, permanent magnet, and the four attaching bolts indicated an axial resonance should occur near this frequency. Care was taken to avoid drawing conclusions about transducer behavior from data taken at frequencies near these structural resonances.

Output forces were calculated via:

$$F = a \times g \times m \qquad (1)$$

where: F = force in Newtons,

a = acceleration amplitude in standard gravities,

$g = 9.807\ \mathrm{m/s^2}$ = standard gravity, and

m = known mass in kilograms.

RMS forces were calculated as:

$$F_{rms} = a_{rms} \times g \times m \qquad (2)$$

Magnetostrictive transducer measurements were performed with three different attached masses, m = 24, 115, and 428 ±0.3 grams, threaded to component (a) of Figure 2. All masses include that of the accelerometer, and threaded connections were greased to reduce relative motion. For the performance comparisons, the permanent magnet and magnetostrictive shakers were tested with one mass, m = 115 grams.

RESULTS

Deviations From Linearity

Figure 4 shows that increasing the drive current with a given mass load increases the output force of the magnetostrictive shaker. In the figure each datum was from 50 averages of acceleration autospectral density functions where the magnitude was reported as that corresponding to the single frequency of sinusoidal voltage/current excitation. Not shown in this plot is the transducer's tendency to increase the relative magnitudes of harmonic frequencies in the output signal (acceleration) with increasing current. This, and other trends in the data, will be addressed shortly. Due to amplifier limits and increasing electrical impedance in the transducer with frequency, curves for the 300 and 400 mA excitation were incomplete. Also, due to the previously mentioned mounting and housing resonances, it is difficult to draw conclusions from the data between 1000 and 4000 Hz.

The datums in Figure 5 were calculated from 50 averages of acceleration and current autospectral densities resulting from broadband pseudo-random voltage excitation. Notice the trend established for the lower rms current amplitudes; rms output force is very nearly linear for currents less than 200 mA_{rms}. In this region of operation the transducer is reasonably well behaved, i.e., it resembles a linear system in the least squares sense. Figure 6 demonstrates this with typical coherence values of greater than 0.99, 0.88, and 0.70 for input rms drive currents of 50, 100, and 200 mA, respectively. The displayed coherence functions were calculated for acceleration from current frequency response functions (or equivalently, force from current). Note the decrease in measurement coherence due to increasing rms current levels. As the currents were increased, the relative magnitudes of the associated harmonics grew disproportionately (recall the discussion of harmonics in connection with Figure 4) causing the coherence of the measurements to decrease.

Increasing the current beyond 200 mA_{rms} yielded still larger relative amplitudes of harmonics, resulting in further degradation of measurement coherence and the nonlinear trend of increased force output displayed in Figure 5.

Taken together, Figures 4 (above 4000 Hz), 5, and 6 confirm the sort of behavior one might expect from an electromechanical transducer employing Terfenol-D as the motion source: it is linear for "low signals" (Clark, 1980; Hunt, 1982). In this linear range it is operating in stable minor hysteresis loops, totally enclosed by the major hysteresis loop of the material.(Hall and Flatau, 1993) Recall Figure 1, a sketch of the major hysteresis loop of Terfenol-D for strain from applied magnetic field strength. The figure could also be viewed as the major hysteresis loop for transducer output displacement from input electric current (displacement approximately equals strain times the length of the Terfenol-D rod, and field strength approximately equals turns per length of the coil times the electric current). Figure 7 is an expanded view of the portion of Figure 1 in which the transducer is typically operated. The distinction between two different minor hysteresis loops and the major loop is illustrated in the figure. All three loops correspond to transducer operation at one very low (near DC) drive frequency.

Recall that the input and output of an ideal linear system are related by a magnitude (or gain) and a phase at any given frequency. A sine wave input yields a sine wave output, oscillating at the same frequency (i.e., no harmonic distortion), modified in amplitude by the gain, and shifted in time by the phase. As a result, a plot of output versus input at a single frequency would be either a straight line or an ellipse, if a relative phase is present in the system. The slope of the line, or the slope of the major axis of the ellipse, would represent the system gain. The width of the ellipse would be determined by the relative phase. Gain and phase of an ideal linear system are functions of nothing but frequency of oscillation.

There are two phenomena to discuss in connection with Figure 7. Both phenomena represent magnetostrictive shaker deviation from linear system behavior. The first is the increase in "effective" slope with increasing current amplitudes. As implied by the figure, the slope at low signal amplitudes is less than the "effective" slope of the hysteresis loop shown for a medium signal. The increased slope acts to disproportionately increase the output at the fundamental frequency of excitation, i.e., the system gain can be a function of drive level. The second phenomenon is the increase in harmonic content as the hysteresis becomes more pronounced. For engineering purposes the low signal minor hysteresis loop is a straight line (or a narrow ellipse), while the medium signal minor hysteresis loop would require that appreciable amplitudes existed in the output at the harmonic frequencies. The increase in harmonic content with increasing current amplitude was reported above in the discussion pertaining to Figure 4, and in Hall and Flatau (1993).

The data from Figure 4 validates the first phenomenon, gain can be a function of drive amplitude, for outputs measured at frequencies below 1000 Hz (away from previously mentioned structural/mounting effects). Specific values of output force, at the fundamental frequency of excitation, from input currents are shown in Table 1. Using the 100 mA values as the reference for each frequency, doubling the current resulted in five times the force, tripling the current yielded approximately ten times the force, and quadrupling the current gave about eighteen times the force. These trends are closer to quadratic than linear because the effective slope of the hysteresis loop is changing with current amplitude. Interestingly, for frequencies of 4000 Hz and above (see Figure 4), doubling the current seems to double the force, tripling the current triples the force, etc. It seems that with increased frequency of oscillation the shaker has evolved to operating in a mode where the effective slope is a constant for a given frequency, at least over this range of drive levels with this load. That is, with increasing frequency of oscillation, the shaker tends to migrate back toward linear system behavior.

When comparing Figures 4, 5, and 6 it is important to note that current amplitudes for Figures 5 and 6 are small compared to those of Figure 4. For Figures 5 and 6, the typical current amplitude at each frequency in the spectrum was less than 5 mA. For Figure 4, single frequency measurements were performed using 100 to 400 mA current amplitudes. Figures 5 and 6 correspond to "low signal" transducer operation. The transducer behavior displayed by the datums in Figure 4 is not that easily classified. Recall, for frequencies below 1000 Hz, the transducer (as loaded) did not behave in a linear fashion; however, above 4000 Hz, it was a better approximation of a linear system.

Broadband Linear Behavior

Standard linear system frequency response functions are presented in this section. Figure 8 shows the electrical impedance of the magnetostrictive shaker, when operated in the linear range with a mass load of 24 grams. It displays all of the classical characteristics of a coupled electromechanical system.(Hunt, 1982) The "unexpected" reduction in electrical impedance magnitude at approximately 8.5-9 kHz is due to the effects of an internal shaker resonance with the 24 gram load attached, plus an external housing resonance (which was apparent in housing accelerations at most loads and drive amplitudes). A great deal of information is available from electrical impedance measurements of transducers. Notice first that the phase seems to reach a maximum of only about seventy degrees. One might legitimately expect the phase to approach ninety degrees since at first glance the electrical circuit looks like it should be primarily resistive and inductive (it is a wound wire solenoid). Note also that the magnitude increases not at 20 but at only 17 dB per decade. Both of these trends are attributable to eddy currents induced in the conductive portions of the magnetostrictive transducer. (No provisions were made to reduce eddy currents within the transducer.) Stoll (1974) explains it roughly as follows.

Eddy currents act to oppose any change in magnetic field. Their effects increase with frequency and tend to reduce the net magnetic flux in the circuit. Since electrical inductance is simply the net flux linkage divided by the impressed electric current, a reduction in inductance with frequency can be expected. Eddy currents are electric currents which flow in conductors of finite resistance; therefore, there are ohmic losses associated with their presence. These losses appear as an increase in the measured resistance with frequency. The net result is that one sees two effects of eddy currents with increasing frequency: a reduction in the measured inductance and an increase in the measured resistance. Referring again to Figure 8, the phase of the electrical impedance approaches a maximum of only seventy degrees because of the interplay of frequency, inductance, and resistance, i.e., $\omega L/R$ (circular frequency times the inductance divided by the resistance) reaches its maximum value instead of increasing with frequency. (Recall, phase is calculated as the imaginary divided by the real component of the impedance, $Z(\omega) = R + j\omega L$, in standard nomenclature, thus, the phase angle is equal to the arctangent of $[\omega L/R]$.) The stunted growth in magnitude, 17 versus 20 dB per decade, is literally because, in the presence of eddy currents in this application, $(R^2 + (\omega L)^2)^{1/2}$ increases more slowly than ω.

The frequency response function as Newton per volt for the magnetostrictive shaker with a 24 gram mass load is shown in Figure 9. Similar traces, only as Newton per amp, are shown in Figure 10. Both measurements were performed with broadband voltage excitation and $i_{rms} = 50$ mA. These measurements represent operation of the magnetostrictive shaker in the linear range with mechanical resonance occurring at approximately 8800 Hz. The aforementioned 9 kHz housing resonance is again apparent in these plots. Recall that the modal analysis of the transducer revealed the likely causes of the fluctuations near 1500 Hz and between 2500 and 3800 Hz to be due to mounting and housing oscillations, respectively.

Recall from linear system analysis that a simple first order system will vary ±90 degrees in phase, a simple second order system varies ±180 degrees, and a third order varies ±270. Note how the phase varies in Figures 9 and 10. For the force per volt frequency response function, Figure 9, the phase varies from -180 to -430 degrees, a change of about 250 degrees, indicating behavior typical of a system of approximately third order. The phase of force per amp, Figure 10, varies from -180 to approximately -360 degrees, exhibiting behavior typical of a second order system (going through -180 - 90 = -270 degrees near the mechanical resonance). Figures 9 and 10 begin at -180 degrees because displacement and current are in phase at low frequencies, force is in phase with acceleration in these figures (it was a mass load), and acceleration lags displacement by 180 degrees.

Figure 11 is a plot of displacement from current as a function of frequency. Values were calculated by dividing the datums of Figure 10 by minus the square of the corresponding circular frequency. As shown in the figure, the magnetostrictive shaker behaves like a second order system. Further, it seems to be a reasonable approximation of the classic vibration model of a forced mass-spring-damper system.

Dynamic Performance Comparisons

Performance of the magnetostrictive transducer was compared to that of a Bruel & Kjaer, model 4809 vibration exciter. Physically, the two are very different. The Terfenol-D shaker's mass was 0.86 kg versus the 4809's 8.3 kg. The B & K was approximately ten times the volume of the magnetostrictive transducer. The B & K had a table height of about 140 mm; the magnetostrictive shaker built for this study measured 110 mm. B & K specifies a sinusoidal peak force rating of up to 45 N (without forced air cooling) for the 4809. The Terfenol-D shaker does well in the force department. Miller (1991) reports clamped forces (at one amp DC) in excess of 140 N from Terfenol-D rods (6.35 mm x 51 mm, using a similar coil). This shaker produced 110 N at frequencies greater than 4000 Hz with a maximum harmonic amplitude of about 3 percent of the fundamental's. (This force rating actually compares well with the next larger B & K, the 35 kg 4808, at 112 N.) Maximum bare table acceleration for the B & K is rated as approximately 100 times gravity. The magnetostrictive shaker in this study regularly produced accelerations double that, with 24 grams of mass load, e.g., 220 times gravity at 5 kHz with sinusoidal excitation.

For the tests that follow, both vibration sources were mass loaded with 115 grams and excited with broadband pseudo-random voltages. Table 2 shows a comparison of rms force output of the magnetostrictive vibration source with a B & K 4809 vibration exciter. The results are listed by drive current values. Note that for a given current, the Terfenol-D produced approximately three times the force of the permanent magnet shaker. There were two separate sets of tests of roughly equal input powers. In both of these cases the Terfenol-D shaker output force exceeded that of the B & K.

Figure 12 displays the major difference in the broadband acceleration characteristics of the two shakers. For this figure, shaker excitations were adjusted such that approximately the same rms accelerations were produced by each (note that the Terfenol-D shaker was operating in its linear region for this test). As shown in the figure, the two shakers exhibited resonances at about 5 kHz, with the amplitudes at frequencies above resonance better maintained by the magnetostrictive shaker. With this in mind and recalling the linear behavior above 4 kHz shown in Figure 4, it seems this magnetostrictive shaker displays its greatest potential (high forces and linear behavior) at the higher frequencies (f > 3 or 4 kHz). Acceleration amplitudes at frequencies below the resonance in Figure 12 were maintained better by the permanent magnet B & K. This trend seems reasonable when you note that the B & K was capable of maximum peak displacements of 8 mm while the magnetostrictive shaker was limited to approximately 0.013 mm. Larger amplitude displacements were possible with the magnetostrictive shaker if harmonic accelerations of approximately the fundamental's amplitude were permissible. (Attaining the larger amplitudes would have required much larger current values, i.e., approaching an amp, as opposed to milliamps.)

CONCLUSIONS

The results demonstrate the characteristics of Terfenol-D as a broadband vibration source. Frequency response functions were shown to give the reader a feel for how a magnetostrictive transducer behaves in its linear region of operation. Of particular interest is that the output displacement from input current behaves like a second order system. Depending upon the drive levels imposed, the magnetostrictive shaker will either behave in a linear fashion or display the characteristics of a nonlinear system (relatively large magnitude harmonics being produced). At the lower drive frequencies (say 30 Hz to about 2 kHz), the shaker built and tested produces low forces and is easily driven into significant hysteretic and nonlinear behavior. Conversely, large forces and reasonable linearity are displayed at the higher operating frequencies (say 4 to 10 kHz). While operating in its linear range the Terfenol-D shaker produces force levels comparable with those of a conventional permanent magnet shaker (B & K 4809). Thus, the "low signal" linear range of the magnetostrictive shaker extends to useful levels of performance. In addition, amplifier requirements for linear range operation are easily met (recall that a standard audio amplifier was used for these tests). The magnetostrictive shaker described represents a viable alternative to commercially available devices for meeting a range of vibration excitation needs.

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Figure Captions

Figure 1. Schematic of strain versus applied magnetic field for Terfenol-D showing the concepts of hysteresis and offset magnetic field, H_o. This is the major hysteresis loop of the material in the sense that it is that which would be obtained by taking the material to saturation at both magnetic limits at, say, 0.1 Hz.

Figure 2. Top view and section of Terfenol-D transducer. Component (a) provides the mechanical output of the transducer, input electrical leads are not shown.

Figure 3. Schematic of experimental set-up.

Figure 4. Magnetostrictive shaker output force at fundamental frequency versus frequency of sinusoidal excitation at specified drive current amplitudes. Mass load = 428 grams.

Figure 5. Output force (rms) versus input current (rms) for the magnetostrictive transducer with a 24 gram mass load. Datums from 50 averages each of autospectral density functions. Measurements were obtained using broadband pseudo-random voltage excitation. Line was fit by eye to demonstrate the deviation at higher current values.

Figure 6. Coherence functions for acceleration/current frequency response functions for the Terfenol-D transducer with rms currents of: 50 mA, 100 mA, and 200 mA. The degradation in coherence with increasing drive current indicates the disproportionate increase in harmonic amplitudes in the output acceleration spectrum. Note that the ordinate limits are 0.5 to 1.0.

Figure 7. Schematic representation of relationships between major and minor (displacement vs. current) hysteresis loops for a magnetostrictive transducer operated at one very low (near DC) frequency. More on this in Hall & Flatau (1993).

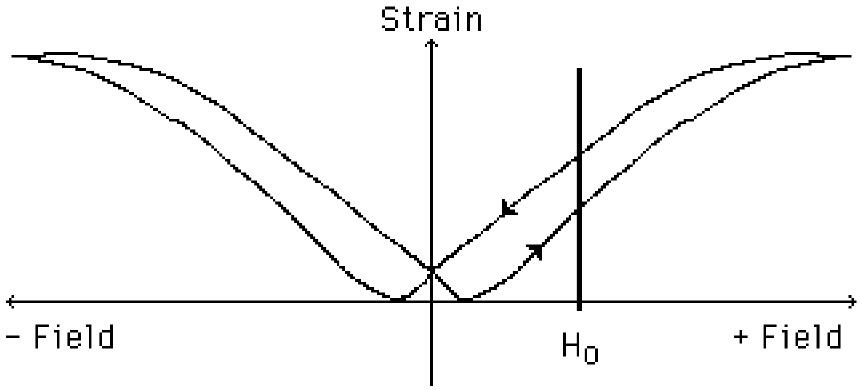
Figure 8. Electrical impedance for the Terfenol-D shaker with mass load = 24 grams. Measurement was obtained using broadband pseudo-random voltage excitation.

Figure 9. Frequency response function as Newton per volt for the magnetostrictive shaker (in the linear range of operation). Input was broadband voltage, i_{rms} = 50 mA, and mass load = 24 grams.

Figure 10. Frequency response function as Newton per ampere for the magnetostrictive shaker (in the linear range of operation). Input was broadband pseudo-random voltage, i_{rms} = 50 mA, and mass load = 24 grams.

Figure 11. Magnetostrictive shaker output displacement from input electric current frequency response function. Datums were calculated from those of Figure 10.

Figure 12. Comparison of acceleration autospectral density functions for the Terfenol-D shaker and the B & K 4809 permanent magnet shaker. Broadband pseudo-random voltage input, B & K: 0.63 V_{rms}, 200 mA_{rms}; magnetostrictive: 2.19 V_{rms}, 58 mA_{rms}. Note: the two input powers are not the same.



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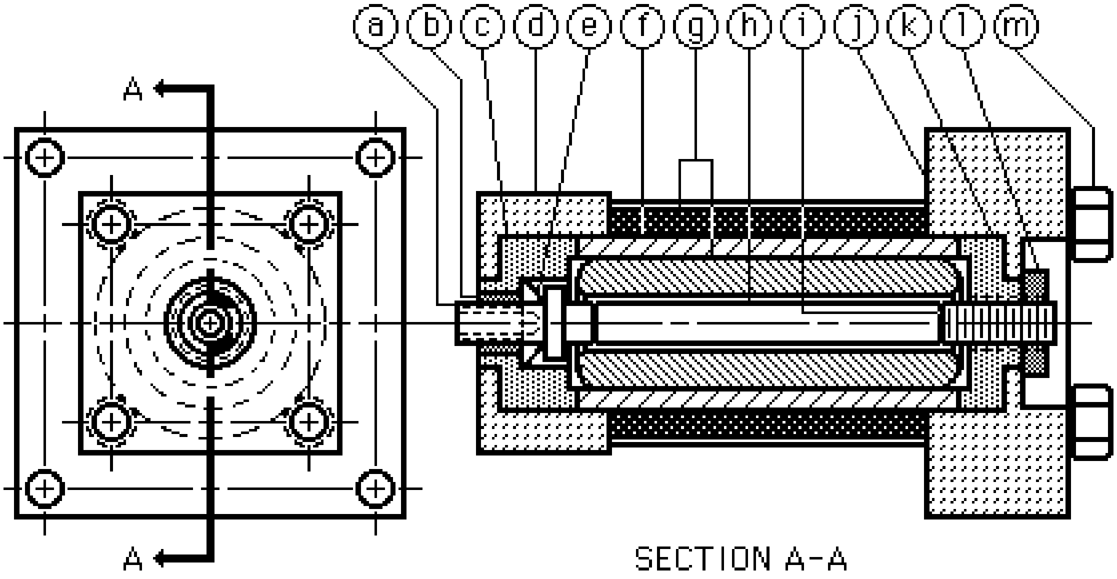

a	1020 steel vibrating mass
b	bronze bushing
c	1020 steel spring seat
d	aluminum housing top
e	Belleville spring washers
f	cylindrical permanent magnet
g	wound wire solenoids
h	Terfenol-D rod, 6.35 x 51 mm
i	prestress adjusting screw
j	aluminum housing base
k	1020 steel adjuster seat
l	jam nut
m	housing bolts (4)

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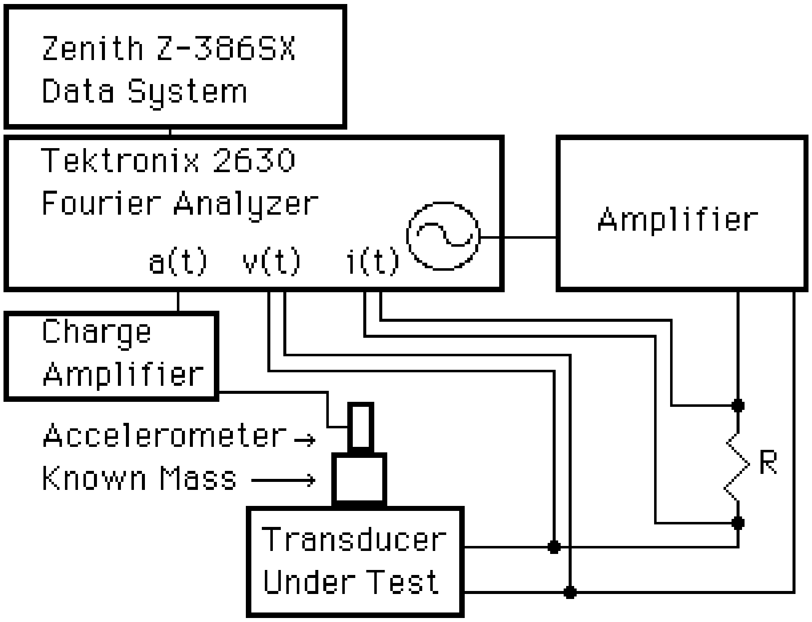

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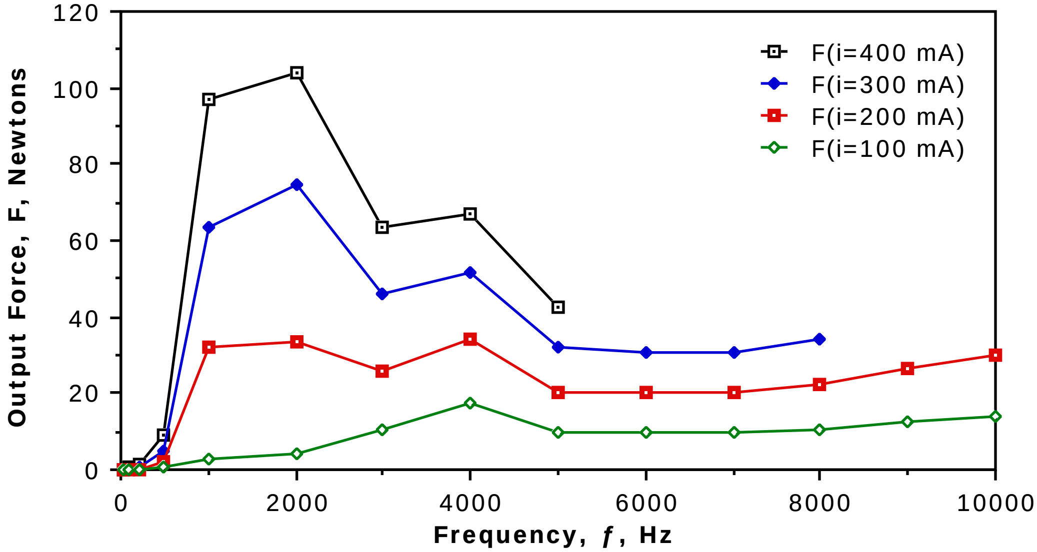

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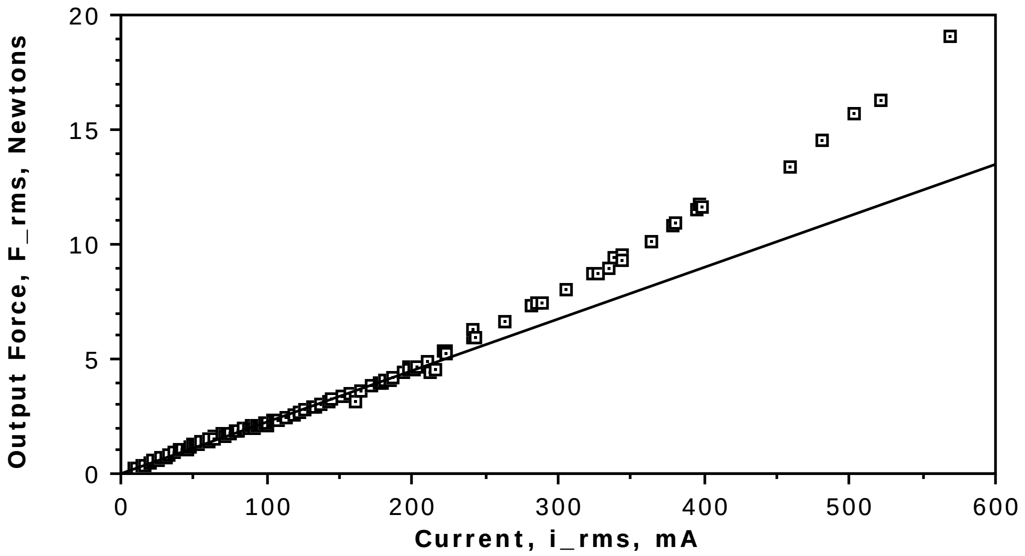

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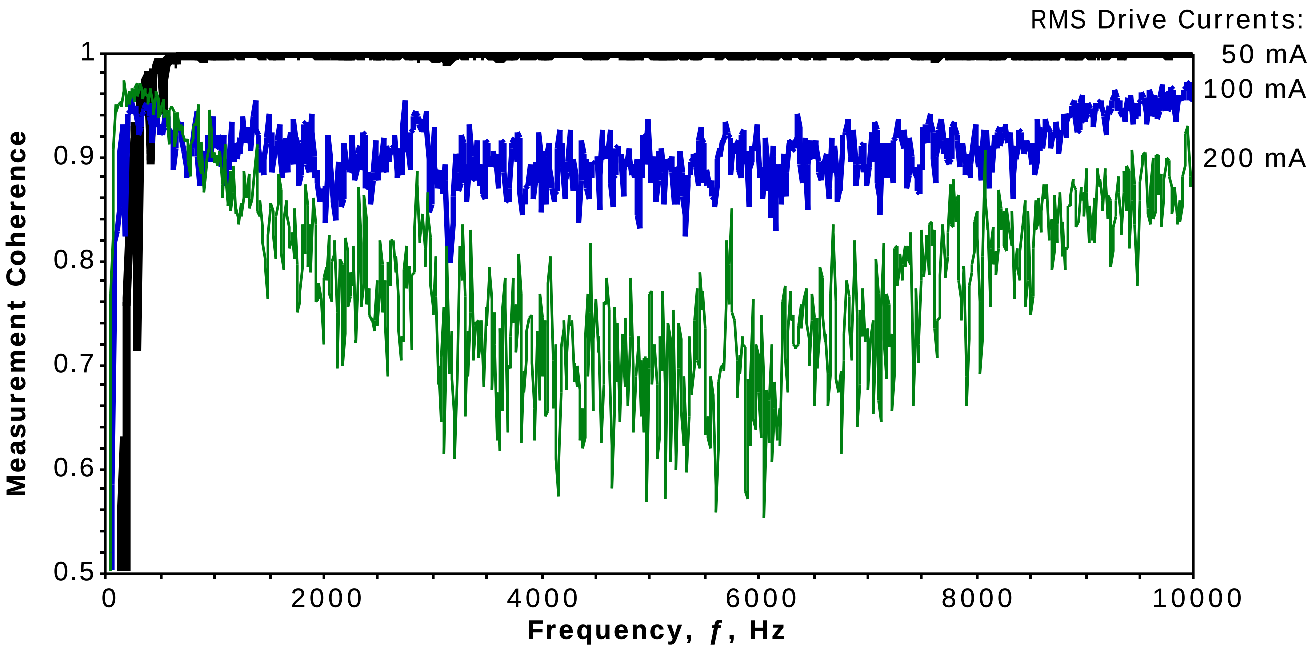

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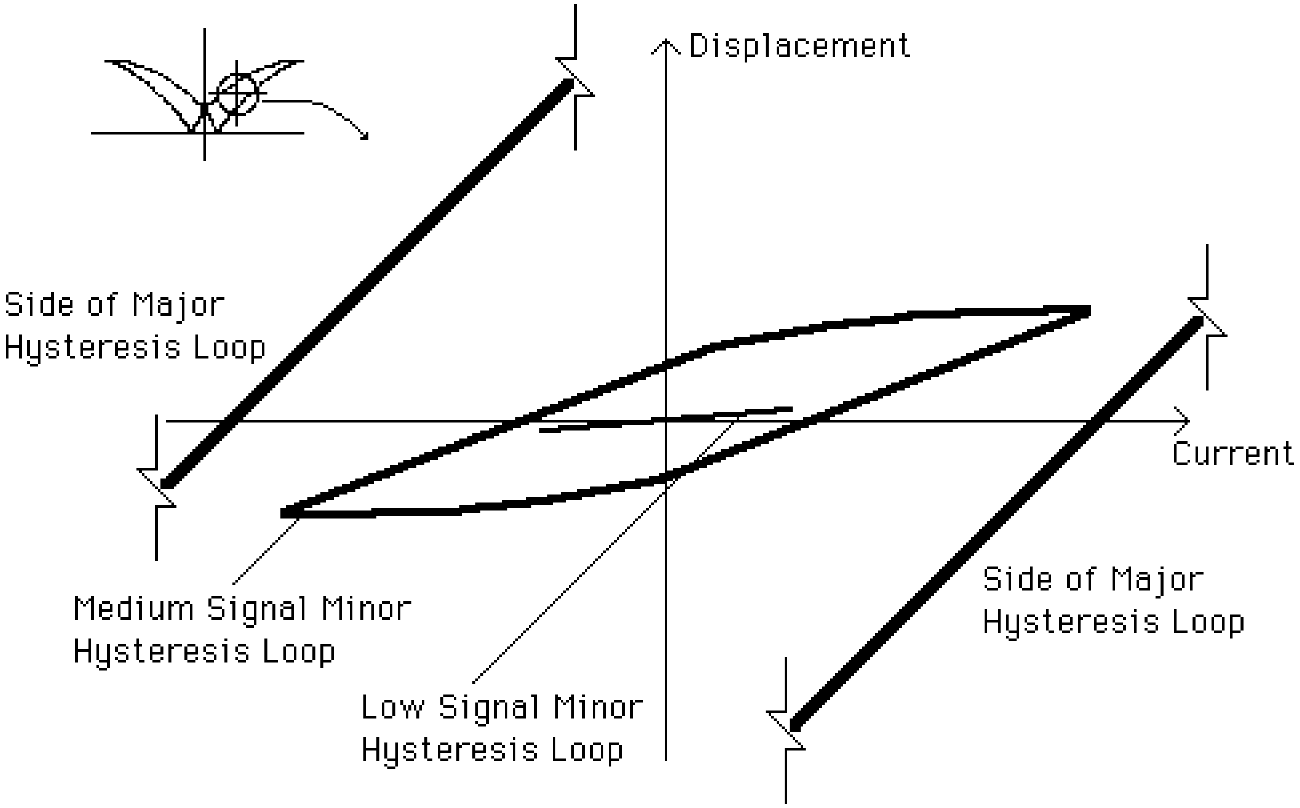

Figure 7. Schematic representation of relationships between major and minor (displacement vs. current) hysteresis loops for a magnetostrictive transducer operated at one very low (near DC) frequency. More on this in Hall & Flatau (1993).

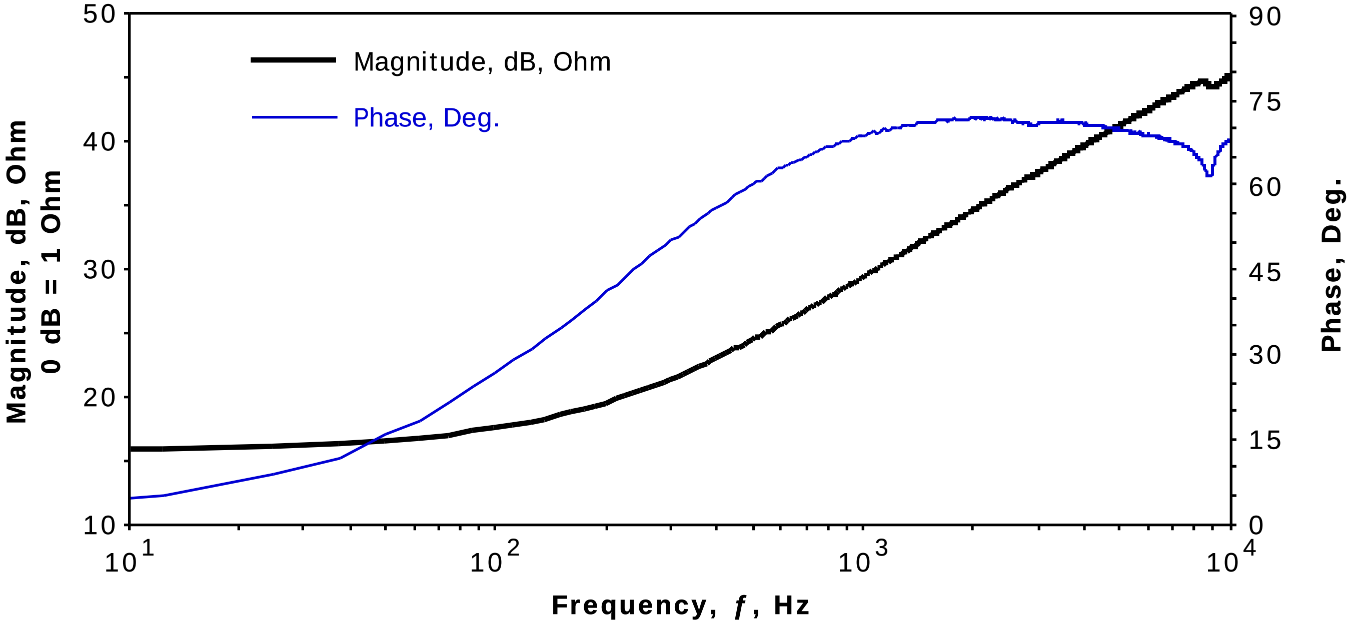

Figure 8. Electrical impedance for the Terfenol-D shaker with mass load = 24 grams. Measurement was obtained using broadband pseudo-random voltage excitation.

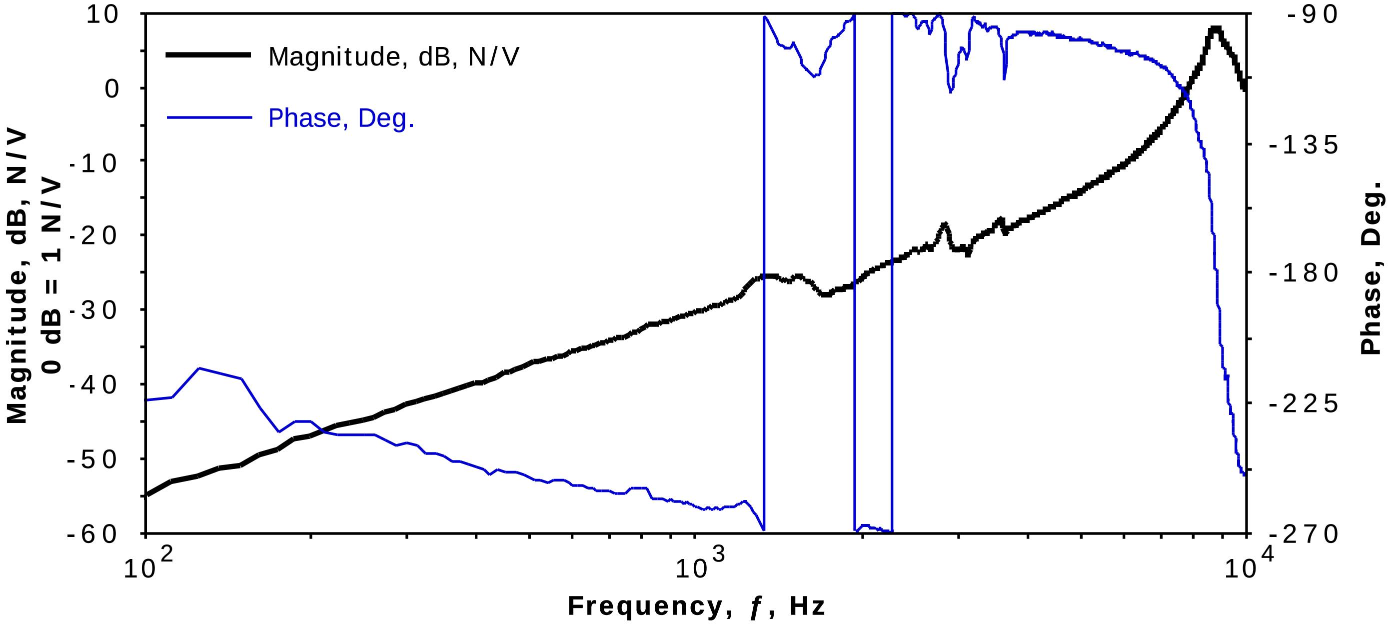

Figure 9. Frequency response function as Newton per volt for the magnetostrictive shaker (in the linear range of operation). Input was broadband voltage, i_{rms} = 50 mA, and mass load = 24 grams.

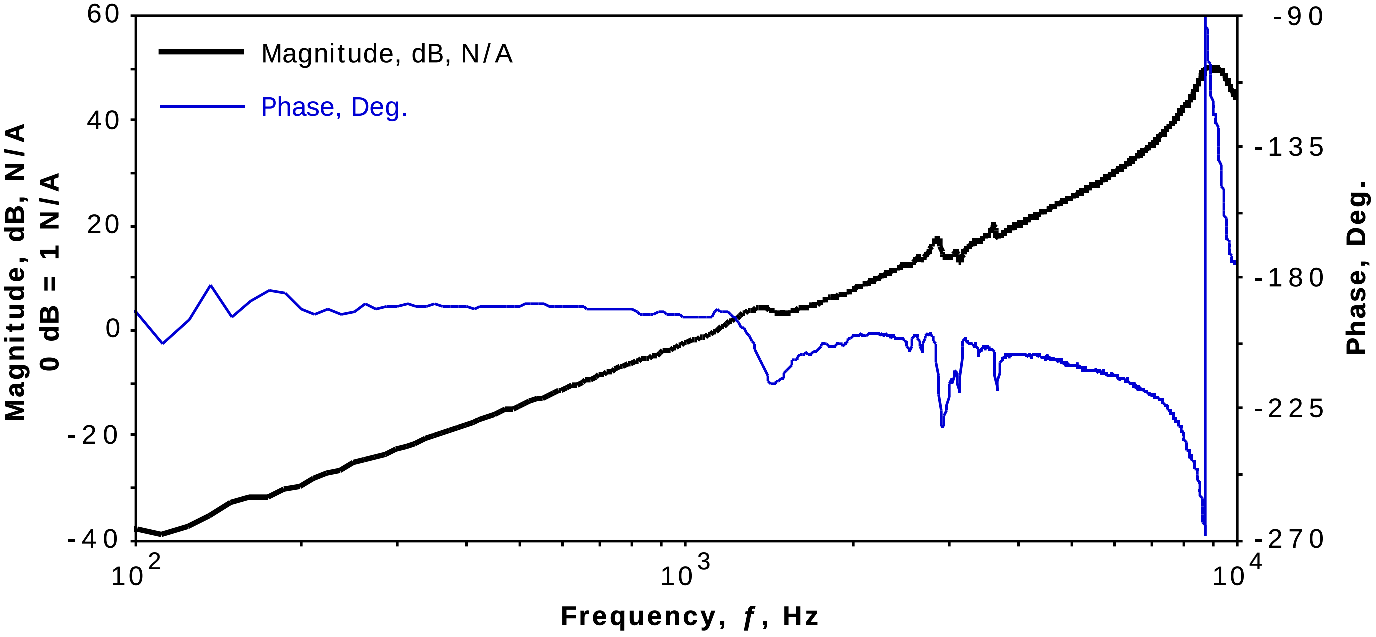

Figure 10. Frequency response function as Newton per ampere for the magnetostrictive shaker (in the linear range of operation). Input was broadband pseudo-random voltage, i_{rms} = 50 mA, and mass load = 24 grams.

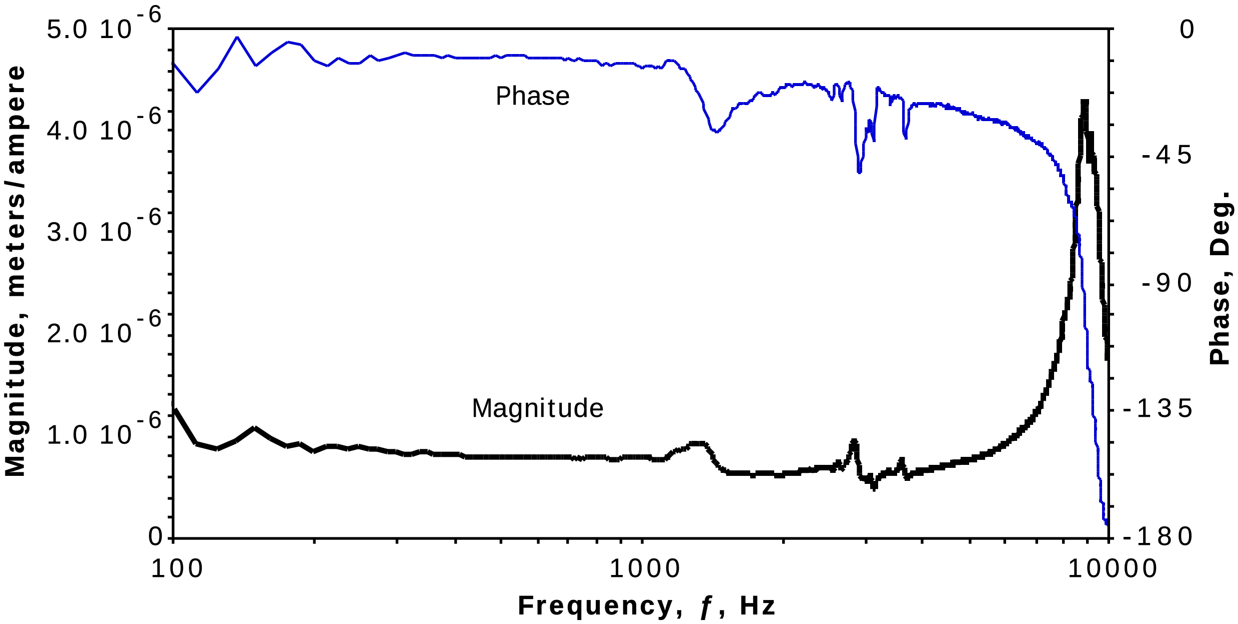

Figure 11. Magnetostrictive shaker output displacement from input electric current frequency response function. Datums were calculated from those of Figure 10.

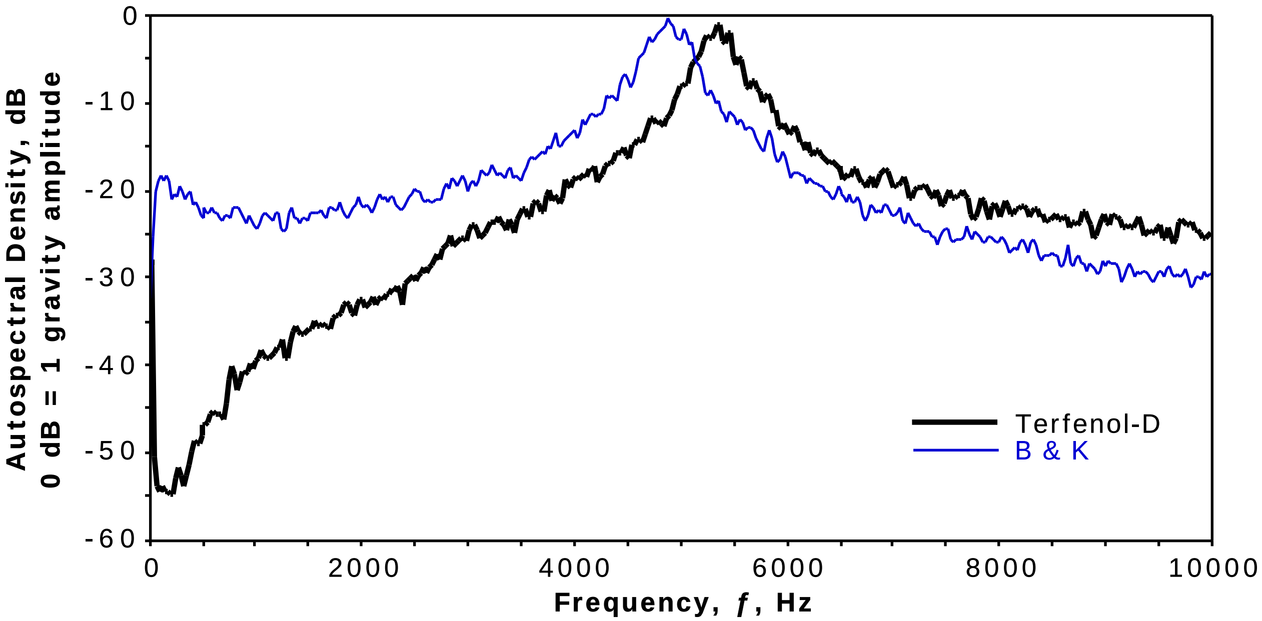

Figure 12. Comparison of acceleration autospectral density functions for the Terfenol-D shaker and the B & K 4809 permanent magnet shaker. Broadband pseudo-random voltage input, B & K: 0.63 V_{rms}, 200 mA_{rms}; magnetostrictive: 2.19 V_{rms}, 58 mA_{rms}. Note: the two input powers are not the same.

Table 1. Partial listing of force as a function of drive current, F(mA), from data plotted in Figure 4.

Frequency, f, Hz	F(100 mA), N	F(200 mA), N	F(300 mA), N	F(400 mA), N
100	0.02	0.09	0.18	0.36
200	0.07	0.34	0.67	1.3
500	0.40	2.1	5.0	8.8

Table 2. Comparison of rms force output of Terfenol-D magnetostrictive vibration source with B & K 4809 vibration exciter, mass load = 115 grams. Results are listed by rms drive currents.

		Current mA_{rms}	Voltage volts_{rms}	Force Newtons_{rms}
B & K		50	0.16	0.71
Terfenol-D[1]		50	1.9	2.6
B & K[1]	100	0.32	1.5	
Terfenol-D[2]		100	3.6	4.2
B & K[2]	200	0.64	2.9	
Terfenol-D		200	8.0	9.2

Notes: 1 Tests of approximately equal input powers.

2 Tests of approximately equal input powers.

KEY WORDS

Broadband

Harmonics

Hysteresis loops, Major and Minor

Linear

Nonlinear

Magnetostrictive

Shaker

Terfenol-D

Transducer

Vibration Excitor