Passive Vibration Damping with Magnetostrictive Composite Material

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ABSTRACT
This paper describes evaluation of an autonomous-material system tailored for free-layer vibration damping of structural elements. The magnetostrictive particulate composite (MPC) material described has moderate stiffness and minimal temperature and frequency dependence. The composite is created by curing Terfenol particles \(\{\text{Tb}_{(1-x)}\text{Dy}_x\text{Fe}_2\}, 0.2<x<0.7\} \) in a thermoset polymer resin system; during curing, the material is subjected to a constant magnetic field. The cured MPC, under vibratory loading, dissipates energy through hysteresis due to domain-wall motion within the particles. The material has an uncommon combination of stiffness and damping, with modulus near that of fiberglass and loss factor similar to many rubber formulations, and the material exhibits vibration damping capability over wide temperature and frequency ranges. Challenges for design are the material’s load-dependent damping capacity and its low ultimate strength.

The MPC damping mechanism is predictable, and a finite element modeling approach was validated by test. Material evaluation was performed with direct measurements of modulus and loss factor. Both composite and monolithic Terfenol samples were built and tested. Measurements of the MPC formulations showed loss factors of up to 0.1 are achievable. Off-stoichiometric samples, with higher levels of Terbium (Tb) content compared to the standard Terfenol composition, were found to have even higher damping, with peak damping observed at Tb 0.5. Loss factors approaching 0.3 were measured in monolithic, off-stoichiometric material samples. The damping is load-dependent, moderately dependent on temperature, and relatively insensitive to loading frequency. A prototype flexure with MPC damping, based on the patented SoftRide design used for whole-spacecraft vibration isolation, was built and tested. Damping and stiffness matched predictions with a finite element model of the MPC-damped SoftRide isolator.

Keywords: passive damping, magnetostrictive composite material, free-layer damping, Terfenol, magnetostrictive particulate composite, non-linear complex stiffness, direct complex stiffness test

INTRODUCTION
CSA Engineering teamed with UCLA and Fortis Technologies to evaluate an innovative composite material for passive structural vibration damping. The magnetostrictive particulate composite (MPC) material possesses an uncommon combination of stiffness and damping, with a modulus close to that of fiberglass and a loss factor (commonly referenced as tan delta*) similar to many rubber compounds. Magnetostrictive materials are typically used for mechanical actuation, not structural damping. However, the MPC utilizes a property of the material that is undesirable for actuation applications, where hysteretic losses dissipate mechanical energy. An advantage of using the material for vibration damping is its utility over a wide temperature range, compared to common viscoelastic damping materials. Material

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* The loss factor of a material, a measure of material damping, is the tangent of the phase angle by which strain lags stress.
optimization has been performed and various formulations have been characterized for structural damping properties. A damped flexure element was developed that could be used in a range of applications, and a test database of material properties was assembled to support the design of various implementations of MPC vibration damping.

The MPC material is created by suspending magnetostrictive particles in a thermoset polymer resin system, typically a vinyl ester, for curing under a magnetic field. The particles are from the Terfenol family, defined by $\text{Tb}^{(1-x)}\text{Dy}^x\text{Fe}_2$, (0.20 $< x < 0.67$); Terfenol is used for mechanical actuation because of its magnetostrictive properties. Under vibratory loading of the cured MPC, hysteresis develops through domain wall motion within the particles, resulting in dissipation of energy and damping of the vibration. Material compositions and manufacturing processes were studied with the objective of optimizing passive damping performance. With damping as an objective, rather than actuation, requirements for Terfenol material composition and fabrication are much less stringent. Particle stoichiometry was also varied, over the range of the Terfenol family, defined by $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$, with $x$ varying from 0.20 to 0.67. The commonly used Terfenol-D has a Tb content of 0.33. During the course of the work, a fabrication facility was setup to fabricate larger sample sizes of all three MPC types.

Evaluation of damping was based on the material property referred to as loss factor ($\eta$), commonly known as tan $\delta$ (tangent of the phase angle $\delta$). In a material such as the MPC that dissipates energy, the strain lags the stress by this phase angle. This material behavior can also be expressed in terms of the complex modulus, or the ratio of the dynamic stress to the dynamic strain. The complex modulus has a real component (storage modulus $E'$) and an imaginary component (loss modulus, $E''$). The ratio of the loss and storage moduli is the loss factor, $\eta$, i.e., $\tan \delta = E''/E'$. Testing of MPC material formulations showed loss factors of up to 0.1 are achievable. The damping is load-dependent, moderately dependent on temperature, and relatively insensitive to the frequency of oscillation. Off-stoichiometric samples with higher levels of Terbium (Tb) content were shown to provide higher damping levels than specimens with the standard Terfenol composition, with peak damping observed at Tb 0.5. Loss factors up to 0.3 were measured in off-stoichiometric samples of monolithic material that were grown by the free standing zone melt (FSZM) method.

Several goals were achieved during the evaluation program in optimization of material formulation for damping, characterization of damping capability and load amplitude dependence, and implementation of a finite element modeling approach. A prototype structural element using MPC damping, based on a patented flexure element used for whole-spacecraft vibration isolation, was built and tested for correlation with a finite element model of the element.

## 1 MATERIAL FABRICATION AND PROCESSES

Manufacturing of Terfenol and MPCs had the objective of optimized passive damping properties. Two processes were used to manufacture monolithic Terfenol compositions from which the particles are manufactured: modified Bridgman growth and arc melting. The principal difference between the two methods is that the Bridgman growth (Etrema Crystal Growth and FSZM) produces textured polycrystalline rods and the arc-melt method produces randomly oriented polycrystalline material. The much-less-expensive arc melting method produces material without any specific crystallographic orientation. In addition to the lack of orientation, the arc-melted sample is considered a cruder process that introduces a substantially larger number of defects. These defects are undesirable when using Terfenol for actuation, but they are acceptable when the material is used for damping applications.

### 1.1. Particle Fabrication

Three different Terfenol rod fabrication approaches were used to manufacture MPC particles, as shown in Figure 1. Etrema Crystal Growth (ECG) rods are produced using a seed crystal to pull out a preferentially aligned rod of the material. The free standing zone melt (FSZM) process is typically employed for producing small batches of off-stoichiometric compositions with preferentially aligned grains. The arc melt technique is the cheapest of these three procedures; it utilizes an electric arc to melt raw material to form the final alloy. Fibrils were cut from ECG and FSZM rods; powder forms were also ball milled from these materials. The arc melt materials were used to form Terfenol powders. In the ball-mill process, the material is placed in a vessel made of a hard substance (either stainless steel or ceramic) along with spherical impact balls. The vessel is sealed and reciprocated at 30 Hz, thereby producing large impact forces and fracturing the material. Due to the Terfenol brittleness, a large 100-gram rod may be ground into powder of less than 300-micron dimension in a few minutes. Bulk Terfenol-D quickly oxidizes in air at room temperature: precaution must be taken to store and manufacture the powder in an inert atmosphere such as nitrogen or argon. Figure 1 shows microphotographs of particulates used in magnetostrictive composite fabrication. Six
compositions of the arc melt Terfenol material \( (\text{Tb}_{(x)}\text{Dy}_{(1-x)}\text{Fe}_{(2)}) \) with Terbium content of 0.35, 0.4, 0.45, 0.5, 0.75, and 1.0 were studied. ECG and FSZM compositions with Terbium contents 0.33, 0.4, and 0.5 were also included in this research effort.

Figure 1. Monolithic Terfenol-D materials: a) Etrema crystal growth, b) free-standing zone melt, c) arc melt rod; Magnetostrictive Particulates: a) powders from ball milling, b) fibrils from diamond saw cutting, c) pins from Etrema

1.2. Composite Manufacturing

Casting and injection molding processes were used to fabricate magnetostrictive composites. In the casting process, the magnetostrictive particulate was mixed with the catalyzed resin, degassed and stirred to reduce the amount of trapped air in the mixture. The slurry of resin and particulate was then poured into an aluminum mold coated with release agent, as shown in Figure 2a. Once the cavity is filled with particulate slurry, the mold was sealed with the top cover, taking care to ensure that air was not trapped in the cavity when the cover was secured. The mold was then placed in an electromagnet for particle alignment. The field at the center of the magnets was set to 240 kA/m; this field was found to be sufficient to align the particles into chain structures along the mold length. After the resin gelled, the mold was removed from the electromagnet and placed in an oven for post-cure.

Aligned magnetostrictive particulate (AMP) composites were fabricated with ball milled particles of Terfenol-D, or ball milled particles of off-stoichiometry Terfenol-D using the Bridgeman growth method. Fabrication of CAMP (crystallographically aligned magnetostrictive particulate) composites required an injection mold technique due to the inability of the particulate to rotate in an applied magnetic field once mixed with resin and placed into a casting mold; a photograph of this injection mold is shown in Figure 2b. The CAMP particulates can, however, rotate freely when placed into a mold without resin.

Figure 2. a) Casting mold for AMP samples b) injection mold for CAMP samples

Two resins were used to fabricate the composites. Spurr resin was chosen because of its very low viscosity (60cps), which gave it exceptional penetration qualities. The low viscosity allows the resin to completely coat the particulates and minimizes void formation in the cured composite. The Spurr resin had the lowest glass transition temperature \( (T_g = 60^\circ C) \) of resins that were considered. Another matrix system tried was Dow Chemical 411 C50 epoxy vinyl ester resin. The most important of its processing properties are its low room temperature viscosity of 50 centipoises and the elastic modulus of roughly 3 GPa; this resin has a \( T_g \) of 120°C.
2 MATERIAL TEST PROGRAM

The main objective of the material test program was to determine material damping capacity of candidate magnetostrictive materials under controlled loading conditions, including sensitivity of damping capacity to material composition, mechanical stress level, loading cyclic frequency and temperature. Several test rigs were used to measure stiffness and damping for various material configurations, and both monolithic and composite specimens were measured. Benchmark testing was performed with a test fixture capable of axial tension-compression loading. Compression-only measurements were performed using an MTS load frame, using (1) constant force with a varying magnetic field, and (2) constant magnetic field with varying axial load through the specimen. Dynamic Modulus Analyzer (DMA) testing was used to characterize specimen dependence on frequency, temperature, and stress level.

2.1 Force-Displacement Measurements

Figure 3 shows the test configuration for benchmarking the DMA and MTS-based results, with axial loading applied to an MPC specimen while measuring the applied force and resulting strain. Axial loading was the preferred approach to benchmark damping characterization data, because the stress state in the specimen is well understood, and the tension/compression state could be controlled. Fixturing with an “align-and-lock” design feature dramatically reduced bending stress levels observed in earlier measurements. The align-and-lock capability was achieved by first tightening one of the four-sided collet chucks, and then tightening the nuts to fix the rod-end bearing alignment while the specimen was loaded in tension. Example axial and bending strain waveforms, depicted in Figure 4, demonstrate the effectiveness of the test technique and fixturing in realizing a stress state with minimal bending.

A servohydraulic actuator was used to apply a controlled sinusoidal load through the specimen. Four linear-pattern strain gages, oriented along the specimen loading direction, provided signals quantifying specimen surface strains. Axial and bending strains were calculated from the four quarter-bridge signals as means and differences from these signals, i.e., the symmetric and anti-symmetric components. A strain-gage-based load cell, mounted on the reaction stiffback, transduced the load through the specimen. Figure 4 also shows a typical measured hysteresis loop with this test configuration. The applied stress is ±10 MPa (1450 psi) and the measured strain is ±700 microstrain. This plot also provides an indication of the frequency independence of the material stiffness and damping. Figure 5 shows damping as a function of peak applied load, for peak stresses of 2 to 16 MPa (290 to 2320 psi) measured on two typical composite material specimens. The material damping load dependence is evident in this plot. This figure also indicates the damping capacity dependence on material composition.

2.1.1 “Instantaneous Loss” Algorithm

A unique feature of the magnetostrictive composite materials is their loss capacity dependence on stress level. In addition to the algorithms developed under this research program to estimate “mean” tan(δ) values, a technique was implemented to characterize “instantaneous” loss capacity. This algorithm was applied to measurements on MPC
specimens under controlled tension/compression sinusoidal loading conditions. The Hilbert Transform was utilized to determine the instantaneous phase of the stress and strain signals by generating the so-called analytic functions. The estimated material loss is derived from the difference between the stress and strain phase angles.

Figure 4. Axial and bending strain time histories, and measured hysteresis loops showing frequency insensitivity

Figure 5. Loss factor as function of peak stress, 2 to 16 MPa - tension/compression tests

Figure 6. Stress/strain Lissajous plot, and instantaneous loss capacity vs. stress

Nonlinear stiffening is evident in the measured stress/strain Lissajous plot (Figure 6); the orbit with quadratic and cubic stiffening terms removed is included on the same axes for comparison. Figure 6 also shows the instantaneous $\tan(\delta)$ as a function of stress, corresponding to the Lissajous measurement display. Estimates of the elastic modulus and $\tan(\delta)$, using the nonlinear optimization approach are included on this figure. The “instantaneous loss” as a function of stress, shown in Figure 6, has a mean value consistent with that resulting from the time domain-based algorithm, which determines best-fit parameters from a sine function basis.
2.2 Magneto-Mechanical Characterization

Magneto-mechanical measurements were made using an MTS load frame. For these tests, samples were strain gaged and encased with a ten-turn coil; Figure 7 is a schematic of this test setup. The sample was placed in the load frame, and the solenoid applied a magnetic field measured with a Hall-effect probe. Applied magnetic field has an equivalent effect to applied mechanical pre-load. Material magnetization was measured in the coil with a flux meter. Rectangular samples milled from arc-melt Terfenol-D (Tb$_x$Dy$_{1-x}$Fe$_2$) rods of varying composition (x = 0.35, 0.40, 0.45, 0.50, 0.75, and 1.0), and two strain gages were attached on opposing sides of the sample, also shown in Figure 7. The resulting signals from the two strain gages were averaged to give a mean axial strain signal. The methodology used by Wun-Fogle at the Naval Surface Warfare Center (NSWC) was adopted in the magneto-mechanical test rig design phase[1]. Measurements were performed at nine magnetic field intensity values ranging from zero to 1600 Oe, in 200-Oe increments, over four compressive stress ranges (1 to 10 MPa, 1 to 20 MPa, 1 to 40 MPa and 1 to 60 MPa). Compression-only loads were used due to the low ultimate strength of monolithic Terfenol-D. The magnetic field set the magnetic domains for subsequent compression cycles.

![Figure 7. Schematic of test configuration for magneto-mechanical measurements; sample cut and strain gaged for cyclic compression test, and test configuration for combined magnetic-mechanical loading tests](image)

The mechanical loading in the MTS load frame was performed with cyclic loading at 1 Hz in this test sequence. The combined magneto-mechanical loading required a novel test setup, also shown in Figure 7. Each test specimen was subjected to compressive loads reacted by ground ends on the two steel rods shown at the left in this figure. The specimen and rods were oriented along the length of the solenoid. The solenoid was water-cooled to minimize unwanted thermal effects on the material sample during the measurement. The steel rods served two functions: 1) they provided the reaction surfaces for controlled compressive stress and 2) the magnetic field lines were concentrated and relatively uniform throughout the test specimen. Magnetic field intensity was measured with a Hall-effect probe inside of the solenoid, near the specimen. Prior to the measurement, a magnetic field of 1800 Oe was applied at near-zero stress in order to orient the material moments along the loading direction. The first compressive loading cycle often differed from subsequent cycles due to resetting of the magnetic moments in the sample.

2.2.1 Magneto-Mechanical Measurements of Terfenol-D

Magneto-mechanical and stress-strain measurements were performed on off-stoichiometric arc melted Terfenol-D samples. Damping capacity in this test sequence was measured at different magnetic field intensities and four peak stress amplitudes of 10, 20, 40 and 60 MPa. Stress-strain plots were recorded while applying a constant magnetic field and subjecting the specimen to compression-only sinusoidal loads. In the methodology used by Wun-Fogle at the NSWC, the damping capacity (ΔW/W) is defined as the absorbed energy (the area of the hysteresis loop in the stress-strain plot) divided by the work stored. Alternative conventions in the damping community have employed work performed rather than work stored. Tan delta (tan δ) is estimated from the damping capacity using the following relation:

$$\Delta W/W = \pi \tan \delta , \quad \delta << 1$$

In these measurements, the work dissipated (ΔW) was calculated excluding the first loading cycle, which is different because of the magnetic presetting of the moments. The work stored (W) was equal to twice the energy from the hysteresis loop centroid to near-zero stress. This approach averaged both loading and unloading segments and effectively shifted the hysteresis loop centroid to the stress/strain origin. A seventh-degree-order polynomial was used to determine the least squares best fit to the loading and unloading segments. The difference between the numerical integral of the loading and unloading segment polynomials was the estimate of dissipated work. The work stored was
determined from the integral of the average of the loading and unloading polynomials, with the limit of integration being to the hysteresis loop center.

Figure 8 depicts estimated loss capacity as a function of magnetic field intensity for a monolithic off-stoichiometric specimen with 0.5 Terbium content. The trend is for the damping capacity to increase with increasing magnetic field intensity to roughly 200 Oe; the loss then drops off with increasing magnetic field intensity. The loss tangent approaches 0.02-to-0.04 at elevated magnetic field intensity levels, as shown in this figure. When exposed to low intensity magnetic fields, the material domains are randomly oriented, resulting in moderate hysteresis. As the magnetic field intensity is increased to 200 Oe, the magnetic domains are partially aligned to the imposed magnetic field; the applied stress then causes a larger percentage of material domain rotations occur than the low magnetic field intensity case. This results in elevated loss factors, approaching 0.16, as shown in Figure 8. With increased magnetic field intensity levels, the imposed mechanical stresses are insufficient to rotate the material domains, which results in lower damping. This figure also illustrates that the dependence of loss capacity on applied peak stress. For low magnetic field intensity levels, lower amplitude stress levels result in higher damping capacity than higher level mechanical loads, while with higher imposed magnetic fields, the highest measured damping capacity corresponds to higher peak stresses. This phenomenon is also attributed to material domain wall motion and material magnetostrictive saturation.

![Figure 8. Tan δ dependence on applied magnetic field and stress amplitude for Tb 0.5](image)

Figure 9 shows elastic modulus results for a Tb 0.5 sample as functions of magnetic field intensity and peak stress level. With no applied magnetic field, the material elastic modulus is highest at the maximum peak stress level. At magnetic fields in the 200-400 Oe range, the measured elastic modulus values reach a minimum; magnetic field intensity above this level results in higher elastic modulus levels. In the low magnetic field conditions, the randomness in the material domains contributes to the sample stiffness due to the domain rotation when mechanical stress is applied. In the moderate field intensity condition (~200-400 Oe), a larger percentage of these domains are aligned with the mechanical loading direction. The domain wall rotation therefore has increased influence on sample elastic modulus (as is its influence on loss capacity); this results in diminished sample stiffness. In the “high” magnetic field conditions, the material domains “are locked” and consequently have less influence on material behavior, thus resulting in the increased material elastic modulus levels.

![Figure 9. Elastic modulus dependence on magnetic field and stress amplitude, Tb 0.5](image)

Figure 10 summarizes loss capacity results from magneto-mechanical tests on monolithic off-stoichiometric specimens with different Terbium contents. Trends observed in the measurements made on the Tb 0.5 sample are consistent with the curves seen in this figure: the damping capacity reaches a maximum at moderate magnetic field intensities. This figure also depicts the dependence of loss capacity on Terbium content. For materials with Terbium contents ranging
between 0.35 and 0.5, the loss factor increases with increasing Tb levels. At the Terbium content of 0.35, the maximum loss capacity is roughly 0.06; at Tb of 0.5, the maximum measured loss capacity approaches 0.14. Materials with Terbium content above 0.5 yield maximum loss capacity lower than the 0.5 Tb formulation, as is shown in Figure 10. A possible explanation is a second phase that precipitates out for materials with Tb content above 0.5, as has been reported by other researchers. Suppression of this second phase may be possible with alternative manufacturing processes. This test sequence indicates that at room temperature, a material system with Terbium content of 0.5 has the maximum damping capacity. Consequently, this formulation became the focus of the research effort.

Figure 10. Tan δ dependence on applied magnetic field and Terbium content

Figure 11 shows the dependence of maximum measured loss capacity as a function of Terbium content for six off-stoichiometric specimens and one free-stand zone melt (FSZM) sample (with Tb = 0.5). This figure shows that the loss factor increases with increasing Terbium content up to 0.5 and decreases with Terbium content above 0.5. The free-stand zone melt sample has a maximum tan(δ) roughly twice as large as the arc-melted sample with the same Tb content (i.e., tan(δ) of 0.3 for the FSZM sample and 0.15 for the arc-melt sample). This may be explained by texturing of the 112-direction in the FSZM specimen. This texturing produces a higher percentage of active domains aligned with the loading direction than the arc melt technique, consequently this results in higher measured loss capacity levels. This result contradicts a hypothesis set forth early on in this research effort: arc-melted formulations would produce higher loss capacity due to embedded anomalies thereby increasing the work required to move a domain past the inclusion. The measurements may indicate that the inclusion is pinned, such that the domain cannot contribute to material loss.

Figure 11. Effect of Tb content on damping properties of monolithic off-stoichiometric Terfenol-D samples

Figure 12 shows damping capacity dependence on peak sinusoidal stress for six off-stoichiometric formulations, measured under a 200 Oe magnetic field. These curves show that the material losses are not monotonic functions of peak stress: there is a stress level that results in a maximum loss. These curves also show that a Terbium content of 0.5 results in damping capacity higher than the other formulations. Thus, the maximum loss capacity is a function of both peak stress and material formulation. Engineering applications of MPC materials can, and perhaps must, be designed using anticipated stresses for the candidate Terfenol-D composite formulations.

Figure 13 depicts the tan(δ) temperature dependence for two Terbium concentrations: off-stoichiometric Tb 0.5 and Tb 0.35. The temperature extremes span –20º to +20º Celsius; these monolithic samples were tested in the MTS load frame using an enclosure to control specimen temperature. Measurements with the Tb 0.5 specimen show minimal temperature sensitivity, unlike the sample with Tb 0.35. It should be noted that viscoelastic damping materials would show strong dependence of loss on temperature within this temperature range. For the Tb 0.35 sample, at temperatures
below 0°C, the loss capacity decreases with decreasing sample temperature. This specimen composition has a magnetic domain state that realigns with a different crystallographic axis at 0°C, this causes the reduction in material damping and the “knee” in the tan(δ) curve. In the Tb 0.5 formulation, there is no crystal-axis realignment between 200°C and -100°C, which results in a nearly constant loss throughout the measured temperature range.

Figure 12. Damping capacity versus stress as function of Terbium composition for H = 200 Oe

Figure 13. Damping versus temperature: Tb 0.50 and Tb 0.35 compositions

2.2.2 Magneto-Mechanical Measurements of Composite

MPC material characterization expanded on the experimental program that studied monolithic magnetostrictive materials. Figure 14 shows estimated loss factors as functions of magnetic field intensity for four composite material compositions. These measurements, conducted in the MTS load frame, subjected each specimen to loads in compression only. This figure illustrates that the material tan(δ) increases with increasing magnetic field intensity below 500 Oe. While similar to that observed for the monolithic materials, these materials exhibit lower sensitivity to magnetic field intensity. With moderate-to-high magnetic field intensities, the tan(δ) decreases with increasing field intensity, as was observed in the monolithic materials. A plausible explanation for this phenomenon based on material science is detailed in Section 2.2.1. Figure 14 also shows the damping capacity sensitivity to Terbium content spanning 0.35 to 0.5. As in the monolithic material measurements, loss capacity of the composite materials increases with increasing Terbium content. In addition to the results from composite materials depicted in this figure, a monolithic resin sample was fabricated and tested in compression-only. Results from the resin-only specimen show a tan(δ) of 0.03; the reduced loss capacity for the composite specimens (relative to monolithic ones) can be explained by a rule of mixtures.

Figure 14. Damping as function of Tb content and magnetic field – composite specimens
2.3 Dynamic Mechanical Analyzer (DMA) Material Characterization

The DMA Q800 was used for measurements on cantilever beam specimens in bending, with no applied magnetic field. Damping was obtained by measurement of the phase angle between stress and strain signals. Monolithic samples could not be tested in the DMA due to the low material ultimate strength. The bending-based material characterization tests showed similar trends that were observed in the compression-only composite material test series. Composite specimens for the DMA test series were fabricated with Terfenol-D particles oriented along the length of the beam sample. The cantilever sample was clamped in a fixture to produce bending. Sinusoidal loads were applied at the specimen free end. Figure 15 depicts tan(δ) results using the DMA system, as a function for peak bending strain for a sample with a 0.5 Terbium content. This figure shows that the loss factor increases with increasing peak strain, with an asymptote of nearly 0.1. The positive slope in the tan(δ) relation is attributed to the increased domain wall motion with higher stress amplitudes. This figure also shows the storage modulus as a function of peak bending strain. The measurements demonstrate that the storage modulus decreases with increasing peak strain from roughly 8 GPa to 6 GPa. The domain wall motion that contributes to sample compliance causes this phenomenon.

The relationship between peak damping capacity and Terbium content, measured in the DMA test series, is shown in Figure 16. As seen in this figure, loss capacity increases with increasing Terbium content for the range below Tb 0.5; the loss capacity decreases with Terbium content in the range above 0.5, as was observed in the compression-only test sequence. These trends can be explained by the increased magnetic anisotropy below Tb 0.5 and the formulation of a second phase of Terbium for the compounds exceeding Tb 0.5.

A series of measurements, using low strain amplitudes, characterized the tan(δ) frequency dependence. Figure 17 shows loss factors for measurements below 100 Hz, for four composite samples in the DMA test machine. Higher strain amplitude measurements yielded larger tan(δ) values than those shown in Figure 17 and had the same trends. Data was not collected above 100 Hz due to influence of fixturing structural dynamics on the results. It is expected that these materials should exhibit a lack of frequency dependence on damping capacity at all frequencies below 1 kHz.

![Figure 15](image1.png)

Figure 15. Damping and storage moduli as functions of peak strain – Tb 0.5 composite under bending condition

![Figure 16](image2.png)

Figure 16. Effect of Terfenol content on maximum damping properties - off-stoichiometric composite samples in bending

![Figure 17](image3.png)

Figure 17. Damping versus frequency - arc melted composites, 5 MPa peak stress
3 DAMPED FLEXURE DESIGN

Building the magnetostrictive damping into a flexure element leverages the material-damping temperature insensitivity. An MPC design demonstration was configured on a patented isolator design, the UniFlex, implementing a free-layer MPC material damping treatment. The SoftRide vibration isolation systems were developed for protection of satellites from launch loads but MPC-damped isolators are not practical for whole spacecraft launch isolation because of the high rocket-motor produced launch loads. However, the UniFlex isolator has also been designed into a strut for more general-purpose vibration isolation and damping applications, and there are potential applications for MPC flexures in environments where the vibration disturbances are in the range of effectiveness for the MPC damping. Spacecraft reaction wheels are one possible application: as spacecraft pointing requirements become more stringent, vibratory loads generated by these wheels require high performance attenuation to reduce effects on the spacecraft bus. The low temperature dependency of the MPC mechanical properties makes this damping system a good candidate for on-orbit vibration isolation.

Several MPC-damped UniFlex flexures were fabricated, using an arc melt MPC composite with a 50% Terbium volume fraction. A finite element model was used to size the isolator and predict the strain energy distribution in the element. The direct-complex-stiffness (DCS) test technique[2] was used to characterize the frequency dependence of the flexure specimen stiffness and loss. This approach processes the load and displacement signals using the fast Fourier transform to derive a complex-valued function of frequency. The MPC-damped UniFlex specimen DCS test used a piezoelectric load cell and eddy current probes to transduce load through and displacement across the test article, respectively. A small electrodynamic shaker provided controlled loading.

A key assumption for the DCS measurement technique is that the specimen exhibits negligible nonlinear load dependence. The nature of the MPC material violates this assumption, resulting in the high variances in loss capacity estimate, as shown in Figure 18. For viscoelastic materials tested using the DCS technique, loss factor variances are much lower than that pictured in this figure, and associated coherence functions are closer to unity than those measured using the MPC-damped flexure. The DCS technique, while sensitive to nonlinearities, will be a tool used by damping and isolation system designers to integrate magnetostrictive composite materials into highly engineered systems. Figure 18 also shows the damped flexure stiffness function, similar to the elastic modulus measured in the DMA-based material test sequence. The stiffness functions show much less dependence on frequency, and much lower variance than the loss factor measurements. The loss and stiffness plots in Figure 18 were measured on two specimens. Loss factor ranged from 0.02 to 0.03 across the 50-Hz measurement band, and real stiffness varied from around 695 lb/in to 725 lb/in. Both stiffness and damping levels measured in the flexure are consistent with material damping measurements.

![Figure 18. Frequency domain loss and stiffness for MPC-damped UniFlex flexures](image)

Stationary sinusoidal load experiments were conducted on the damped UniFlex specimen using a low drive frequency to eliminate fixturing dynamics effects. Figure 19 shows a load/deflection orbit plot measured on a UniFlex flexure with the MPC damping treatment. The measurements, the least squares fit and points in the over-determined set of equations used to derive the loss factor are included for comparison. While fit error is comparatively high at the ends of the

† US Patent #6,199,801 awarded March 13, 2001
loading cycles, the loss capacity estimate accuracy is high as evidenced by the close agreement between the measurement and the fit through the majority of the loading and unloading cycles. Estimate of the damped flexure stiffness – a coefficient in the best-fit ellipse – is consistent with the stiffness predicted by the finite element model.

**Figure 19. UniFlex flexure load/deflection Lissajous plot**

### 4 SUMMARY

Under this program, a unique autonomous-material system was evaluated as a passive vibration damping tool for mechanical design and implemented in a structural damping element. The composite material uses implementations of the magnetostrictive Terfenol family, defined by $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$, $(0.2 < x < 0.9)$, cured into a resin system to create magnetostrictive particulate composite (MPC) materials. The MPC is cured while exposed to a high intensity magnetic field; domain walls are therefore aligned in the cured composite. Under cyclic loading, strain-induced domain wall motions dissipate vibrational energy and generate damping.

Material system evaluation included testing of composite samples as well as monolithic Terfenol specimens. Composites were manufactured and tested using the equivalent Terfenol ‘mixes’ in the specimen. Loss factors of up to 0.1 were achieved in the composite, while loss factors up to 0.3 were measured in off-stoichiometric monolithic material samples. Damping was found to be consistent over a temperature range of at least $-20^\circ$ to $20^\circ$C, and it is not expected to change substantially outside this range. The relatively high MPC stiffness and indications of higher loss factors than those measured (that may be achieved through additional research), will enable this class of materials to be used in damping applications that have few mass-efficient alternatives.

Several applications for this material damping technology have been identified. A flexure similar to ones used in vibration isolation systems was built and tested, using free layer damping with the MPC material. Measurements of the MPC-damped flexure are encouraging, but it will be necessary to increase the amount of damping achievable with the material before it replaces this and similar applications of viscoelastic damping. However, the wider range of temperature over which the damping is achievable is a definite advantage, and will provide some unique applications for MPC damping.

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### 6 REFERENCES

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