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Carderock Division
Naval Surface Warfare Center
Bethesda, Md. 20084–5000

CARDEROCKDIV–MRD–93/25 December 1993
Machinery Research and Development Directorate
Technical Report

Transmissibility of Nickel-Titanium Shape Memory Alloy Springs

by
Edward J. Graesser

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ABSTRACT

A research study was undertaken to measure the transmissibility of nickel-titanium (Ni-Ti) shape memory alloy (SMA) springs and compare the results to corresponding data on steel and Inconel springs. It was motivated by interest in an effective metal alternative to rubber-based machinery isolation mounts, with possible active control features. Ni-Ti was used due to its well known properties of shape memory and high intrinsic damping. Acceleration transmissibility was measured on a spring-mass system. Due to the distributed mass in the spring coils, standing waves occurred at high frequencies. However, due to the high intrinsic damping in Ni-Ti, the standing wave resonance peaks were as much as 20 db lower than corresponding peaks in steel and Inconel springs. Thus the capability of Ni-Ti springs for high frequency vibration isolation is significantly better than that of steel or Inconel. Also, it is judged that the Ni-Ti material could be used in a variety of other isolation mount designs with a high likelihood for further improvement in passive isolation properties. In addition, it may be possible to use the shape memory effect in active control concepts.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

There are numerous applications in which metallic isolation devices can offer definite advantages over rubber or other polymeric mounts/isolation devices. The advantages are most promising in areas where gasses, oils, corrosive agents, and/or especially high temperature or greatly fluctuating heat levels are present.

It is first noted that there are certain disadvantages associated with metal springs as isolation devices, as pointed out by Sykes [1]. From a mechanical vibration standpoint, springs deviate from ideal behavior because secondary resonances are developed at frequencies above the primary natural frequency of the spring-mass system. These secondary resonances are due to standing waves which develop in the spring coils from the combined effects of distributed mass, high stiffness, (generally) low damping, and ease of wave propagation. Indeed, the coils of a spring can oscillate in many modes thus allowing for effective passage of vibrational waves.

However, this acoustic deficiency can be alleviated through proper design and use of a metal with intrinsic high damping and/or damping treatment. Shape memory alloys (SMAs) such as Ni-Ti offer many useful characteristics for vibration isolation and noise suppression including a high intrinsic damping capacity (peak loss factor between 0.02 and 0.04) and a capability for force actuation. The mechanical characteristics and related microstructural phenomena of these alloys are described in many literature sources [2-7]. In SMAs, the martensite transformation is the key to the shape memory effect (SME), and here we offer a brief description of the process. Martensite transformation in SMAs is a crystalline phase change which can be driven either by changes in temperature or by applied stress. Summarily, the martensite transformation is a first order displacive process in which a body-centered cubic (BCC) parent phase (also called SMA austenite phase) transforms by a shearing mechanism to martensite which is both ordered and twinned. The essential details of the transformation are the same in either case, but it is best to explain the thermally driven process first.

In a stress-free condition and above the martensitic starting temperature, M_s, the atoms in the lattice are randomly disposed, or unordered (i.e. the position of atoms in any one unit cell is not necessarily the same for all unit cells in the lattice structure). Upon cooling from such a state, the atoms in the lattice interact with their nearest neighbors and undergo a displacive reorganization, until a preferred arrangement or ordered lattice structure is obtained (i.e. where the arrangement if atoms in one unit cell are representative of all other unit cells in the lattice). This ordered lattice is the result of a free energy minimization. Upon continued cooling to temperatures below M_s, another energy minimization takes place whereby the parent phase spontaneously transforms by a shearing process to a close packed symmetric martensitic phase. With further cooling to temperatures below the fully martensitic temperature, M_f, the microstructure is formed into completely martensitic self-accommodating groups (or platelike variants) which are highly twinned. Between M_s and M_f the martensite takes up a fraction of the material volume (0% at M_s and 100% at M_f); this fraction is known as the martensite phase fraction. With rising and falling temperature the martensite will disappear and reform. And because the entire process is driven by shear, there is no effective change in volume.

The habit plane of transformation from parent to martensite is the (011) plane, which is formed geometrically by the parallel face diagonals of a cube. Because each of the six faces has two diagonals, and due to twinning, there are twenty four possible variants of martensite in SMAs. When holding the temperature below M_f and subjecting the material to an applied stress, these variants (due to their multiplicity) undergo a self-accommodating pattern of shear induced shrinkage, growth, and reorientation when the stress is raised above some critical value. This stress is akin to a plastic yield stress and loading above this stress level leads to potentially large inelastic strains, which are likely to be deviatoric if measured for all three principal directions. A sufficient amount of loading will eventually lead to one single preferred martensite variant for each grain in the microstructure (additional stress will result in elastic loading of this variant). A hysteresis pattern associated with cyclic loading of this type is shown in Fig. 1a.

Unloading from such an inelastic state leaves a residual strain which is, in all aspects, similar to the permanent set after unloading from a plastic stress state in non-SMA metals.

However, in SMAs, this residual strain can be recovered by the shape memory effect, which is induced by heating the volume to a temperature above A_f (A_f is the temperature where the austenitic parent phase becomes fully formed, and it is usually slightly above M_s). This heating generates a reverse phase transformation back to the parent (or memory) phase, and the inelastic residual strain is recovered. It is by this action that actuation forces can be developed.

Now, again starting with the parent phase, but this time holding the temperature constant above A_f, application of stress causes a equivalent process to take place. In this case, the parent phase is present and stable throughout any stress-free sample volume. Subsequent application of stress to levels above a critical value causes completely analogous transformations from parent to martensite phase. Above this critical stress, a long plateau is traced out in stress-strain space, and along this plateau parent-martensite transformations occur simultaneously with growth/reorientation of newly formed martensite variants. Sufficient loading leads to formation of single variants of martensite on a grain by grain basis. Once fully transformed to a grain structure of single variants, additional stress will cause elastic and possibly plastic deformation. This stress-induced martensite (SIM) is metastable however, i.e. stable only due to the presence of applied stress. Stress removal causes the martensite to spontaneously transform back to the parent phase, thus developing a mechanical shape memory. This takes place at a lower stress plateau, therefore giving rise to hysteresis. The total effect is aptly named "superelastic," and is shown in Fig. 1b. Note the clear difference from the type of hysteresis exhibited in plasticity.

Now, an important feature can be inferred with regard to the critical stress value for SIM. When in a stress-free state, martensite forms readily at temperatures just below M_s.

At temperatures higher than M_s, applied stress is necessary to form martensite. Therefore the critical stress for martensite formation is temperature dependent. Finally it should be noted that SIM is possible only up to a critical temperature M_d, above which elastic and possibly plastic deformation will prevail.

The SME as discussed up to this point is referred to as the one-way memory effect; i.e. shape recovery takes place only on heating to above A_f, and no shape changes take place on cooling to below M_s. A two-way shape memory is also possible in which shape changes occur with both heating and cooling. However, two-way memory is not an intrinsic feature of alloy composition alone, but it is the result of careful thermal and mechanical training of one-way SMAs.

The martensite transformation is also the basis for high damping capacity of SMAs. When an SMA is in the martensitic condition, a vibratory applied stress causes relative oscillatory motion of internal twin boundaries thus producing dissipation due to internal friction. The damping is generally independent of frequency (unlike polymeric materials), so that low and high frequency vibrations alike can be controlled or mitigated. These properties of shape memory, superelasticity, and high intrinsic damping have great potential for exploitation in intelligent materials and structural systems.

As a first step in the study of SMAs for use in machinery isolation systems, the transmissibility of springs was measured. If the standing wave resonance peaks of the SMA spring can be significantly reduced over those developed by steel (or other low damping structural metal) springs, then the SMA can be judged to be a good candidate material for new machinery mount designs. The nickel-titanium SMA material, in addition to high intrinsic damping, also possesses an extremely high resistance to corrosion, making it especially suitable to naval applications.

EXPERIMENTAL SETUP AND PROCEDURE

Nickel-titanium springs were made by Shape Memory Applications, Inc. of Sunnyvale, California. Two springs were made: one was made to be in the martensitic condition at room temperature, and the other was made to be superelastic at room temperature. These springs were designed to be tested against a steel spring and an Inconel spring which were available in-house. The SMA springs were designed so that the amount of mass of the active turns in the springs would be close to that of the steel spring. They were also geometrically very similar to the Inconel spring.

Some general material properties of Ni-Ti are given in Table 1. Selected metallurgical data on the Ni-Ti springs are given in Table 2. Selected engineering data on the Ni-Ti, steel, and Inconel springs are given in Table 3. All springs had ends which were squared and ground; therefore the number of active turns in the spring coil is two less than the total number of turns [8].

The experimental setup is shown in the diagram of Fig. 2. The spring to be tested for transmissibility is shown schematically as the parallel spring-damper arrangement with constants k and c respectively. A steel blocking mass was used and is marked by the symbol M. This mass was suspended from above by two soft elastic cords. Thus, the frequency of the suspended mass-cord system was very low ($\sim$ 1 Hz). The spring was joined to the mass on one end and a transducer block on the other; superglue was used to make a strong bond at each end. A Wilcoxn F3 shaker, S, was attached to the transducer block and this device had an internal accelerometer from which to take measurements. A separate accelerometer (Endevco, Model 2217E), **A**, was attached to the blocking mass as shown. A Hewlett-

Packard Dynamic Signal Analyzer, Model 3562A (hereafter referred to as the HP 3562) was used to drive the shaker and monitor/store the vibration response of the system.

Table 1 Properties of Binary Ni-Ti Shape Memory Alloys (from [2])

Melting temperature, °F (°C)	2370 (1300)
Density, lb/in^3 (g/cm^3)	0.233 (6.45)
Resistivity, $\mu\Omega$·cm	
Austenite	≈ 100
Martensite	≈ 70
Thermal conductivity, Btu/ft·hr·°F (W/m·°C)	
Austenite	10 (18)
Martensite	4.9 (8.5)
Corrosion resistance	Similar to 300 series stainless steel or titanium alloys
Young's modulus, 10^6 psi (Gpa)	
Austenite	≈ 12 (≈ 83)
Martensite	≈ 4-6 (≈ 28-41)
Yield stress for SIM, 10^3 psi (Gpa)	
Austenite	28-100 (195-690)
Martensite	10-20 (70-140)
Ultimate tensile strength, 10^3 psi (Mpa)	130 (895)
Transformation temperatures, °F (°C)	-325 to 230 (-200 to 110)
Latent heat of transformation, cal/g·atom (Kj/kg·atom)	40 (167)
Shape memory strain	8.5% maximum

Table 2 Metallurgical Data on Ni-Ti SMA Springs (from supplier)

Composition, Wt %						
	Ni	Ti	C	O	H	Others
Spring 1:	55.40	44.40	0.039	0.064	0.002	0.0951
Spring 2:	55.90	43.90	0.039	0.064	0.002	0.0951
Transformation temperatures after heat treatment, °F						
	M_s		A_f			
Spring 1:	≈ 86		≈ 122			
Spring 2:	≈ 32		≈ 59			
Behavior at room temperature						
Spring 1:	martensitic					
Spring 2:	superelastic					

Table 3 Engineering Data on Springs Used in Test Program

Mean coil diameter *D*, in	
Ni-Ti spring 1:	1.6
Ni-Ti spring 2:	1.54
Steel spring:	1.0
Inconel spring:	1.6
Wire diameter *d*, in	
Ni-Ti spring 1:	0.24
Ni-Ti spring 2:	0.23
Steel spring:	0.23
Inconel spring:	0.22
Number of active turns *N* (total number of turns $N_T = N$-2)	
Ni-Ti spring 1:	6
Ni-Ti spring 2:	6
Steel spring:	8
Inconel spring:	5.4
Spring length *L*, in	
Ni-Ti spring 1:	3.65
Ni-Ti spring 2:	3.9
Steel spring:	2.95
Inconel spring:	3.7
Spring mass *m*, lb (lb·sec²/in)	
Ni-Ti spring 1:	0.399 (1.03×10^{-3})
Ni-Ti spring 2:	0.363 (9.39×10^{-4})
Steel spring:	0.309 (7.99×10^{-4})
Inconel spring:	0.385 (9.95×10^{-4})
Spring stiffness *k*, lb/in	
Ni-Ti spring 1:	49.0
Ni-Ti spring 2:	51.5
Steel spring:	500
Inconel spring:	150

The HP 3562 was configured to make frequency response measurements using a swept-sine input signal to the shaker. An auto-correlation feature and slow sweep rates were used to insure very accurate measurements. The frequency range was from 10 Hz (sometimes 5 Hz) to 5 kHz. All measurements to be presented here displayed highly acceptable coherence functions ($\approx$ 1) across the frequency range. All tests were carried out at room temperature.

TEST RESULTS AND ANALYSIS

The system shown schematically in Fig. 2 can be analyzed from a lumped parameter standpoint as a first approximation for the system response. By doing an impedance-type analysis, and by neglecting the soft elastic cord k_b ($k_b \ll k$) as well as the mass of the spring ($m \ll M$) and mass of the shaker (mass of shaker $\ll M$), the following result for acceleration transmissibility is obtained:

$$\left|\frac{a_2}{a_1}\right| = \frac{\sqrt{\left[1 + (4\zeta^2 - 1)\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + 4\zeta^2\left(\frac{\omega}{\omega_n}\right)^6}}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2} \tag{1}$$

where

$$\omega_n = \sqrt{\frac{k}{M}} \qquad \zeta = \frac{c}{2\sqrt{kM}} \tag{2}$$

Here, ω_n is the primary natural frequency of the spring-mass system, and ζ is the damping ratio; i.e. the ratio of viscous damping c to the critical damping $c_c = 2\sqrt{kM}$.

The above transmissibility equation is a description of an ideal spring-mass-dashpot type of system. A plot of the equation is given on a decibel (db) scale in Fig. 3 for different values of damping ratio. Note that a quantity x in db is determined by $20 \cdot \log_{10} x$. A number of trends are observed. First, for low damping (solid curve), a large resonance peak is developed. At higher frequencies this peak is followed by a 12 db per octave reduction in transmissibility. Addition of damping suppresses the resonance peak, but also lowers the rate at which transmissibility drops at high frequency.

In actual springs, secondary resonances are manifested due to standing waves which are developed in the coils. These are shown in a schematic plot on Fig.4. Note that the separate traces are all for the same spring, but with different amounts of blocking mass. As mass is increased, the frequency of primary resonance is reduced while the frequencies of secondary resonances remain unchanged. This happens because the secondary resonances are dependent only on the spring stiffness k and the mass m of the spring. This was pointed out by Harrison et. al in [8]. Indeed, the equation for approximation of the standing wave resonance frequencies was given in [8] as follows:

$$\omega_i = i\,\omega_n \pi \sqrt{\frac{M}{m}} \qquad i = 1, 2, 3, \ldots \tag{3}$$

And using the Eq. (2) for ω_n, this expression becomes

$$\omega_i = i\pi \sqrt{\frac{k}{m}} \qquad i = 1, 2, 3, \ldots \tag{4}$$

Test results for the steel, Inconel, Ni-Ti martensitic, and Ni-Ti superelastic springs are given on Figs. 5-8, respectively. In Fig. 5 for steel note the particularly strong secondary resonances starting at around 400 Hz. This first standing wave frequency is nicely predicted by Eq. (4) as are the subsequent secondary frequencies. The transmissibility result for Inconel in Fig. 6 shows very similar characteristics as in Fig. 5.

The transmissibility traces for the Ni-Ti springs also show secondary resonances in Figs. 7 and 8, but with much lower heights in their peaks. When matching curves on a peak by peak basis and overlaying corresponding peaks, the secondary resonances developed by the Ni-Ti springs are consistently lower than corresponding peaks for the steel and Inconel springs by 10 to 20 db. The Ni-Ti martensitic spring outperforms its superelastic counterpart by a small margin due to its somewhat higher intrinsic damping.

Rubber-based machinery isolation mounts used by the Navy generally do not display the high frequency transmissibility characteristics seen in metal coil springs. This is because Navy mounts are designed to put the high damping rubber into a deformed state which is almost entirely shear for either axial or radial loading. Even so, the transmissibility characteristics of Ni-Ti SMA springs may be good enough to warrant use in certain applications where rubber-based mounts degrade due to heat, oil, coolant products, or other potentially harmful agents. Such agents will not adversely affect Ni-Ti. Furthermore, rubber-based mounts drift due to creep effects induced by load and deformation. A metal based mounts would not exhibit the effect of drift to nearly the same extent.

On a material basis alone, the nickel-titanium shape memory alloy springs exhibit transmissibility properties which are superior to common metal springs made from steel and Inconel. This is an important acoustic result. The Ni-Ti SMA also offers adaptive material characteristics: namely shape memory. Furthermore, the SMA can be used as a sensor since resistivity changes with stress. Therefore it may be possible to construct an effective mount or isolation device using SMAs with sensing and/or actuation capabilities. These are advanced concepts worthy of focused study.

CONCLUSIONS

It is emphasized that a very significant improvement in acoustic transmissibility of lightly loaded springs is realized by use of the Ni-Ti SMA as a spring material. It is judged that very effective isolation mounts can be designed with the SMA material, and that springs are but one possible type of mount. Even better designs could be made by incorporating annular leaf spring concepts or SMA wire rope designs, among others. An SMA cable made like wire rope could be doubly effective from a damping perspective since damping would arise from two sources: SMA intrinsic damping and inter-fiber friction due to relative motion between cable fibers. Furthermore, an SMA isolation device or mount could be made to include the important features of sensing, stiffness adaptation, and/or force actuation. A truly "intelligent" mount would integrate all these characteristics with a control algorithm. It is noted, however, that these concepts require much more study including further research, development, and testing of various design ideas and concepts.

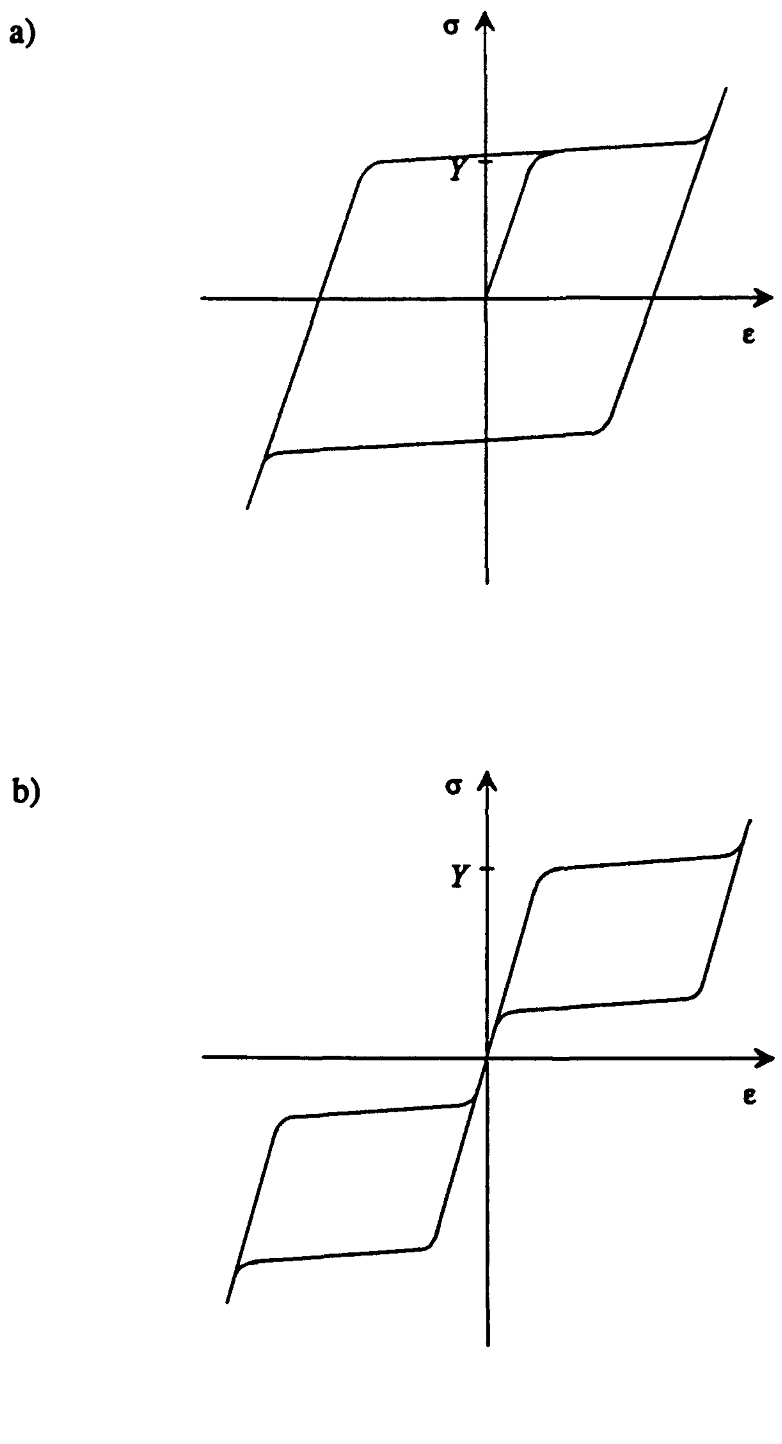

Fig. 1 Schematic Stress-Strain Curve of Shape Memory Alloys

(a) at temperatures below M_f: twinning hysteresis
(b) at temperatures above A_f: superelasticity

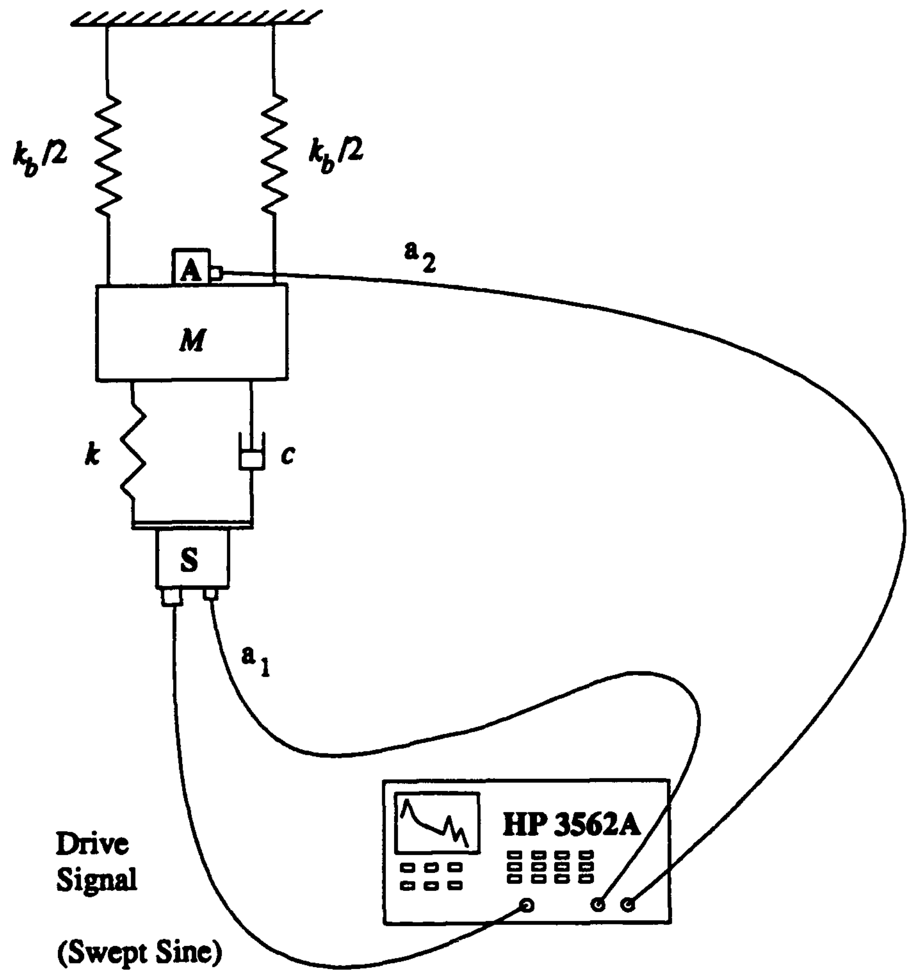

Fig. 2 Schematic of Vibration Test Set-Up

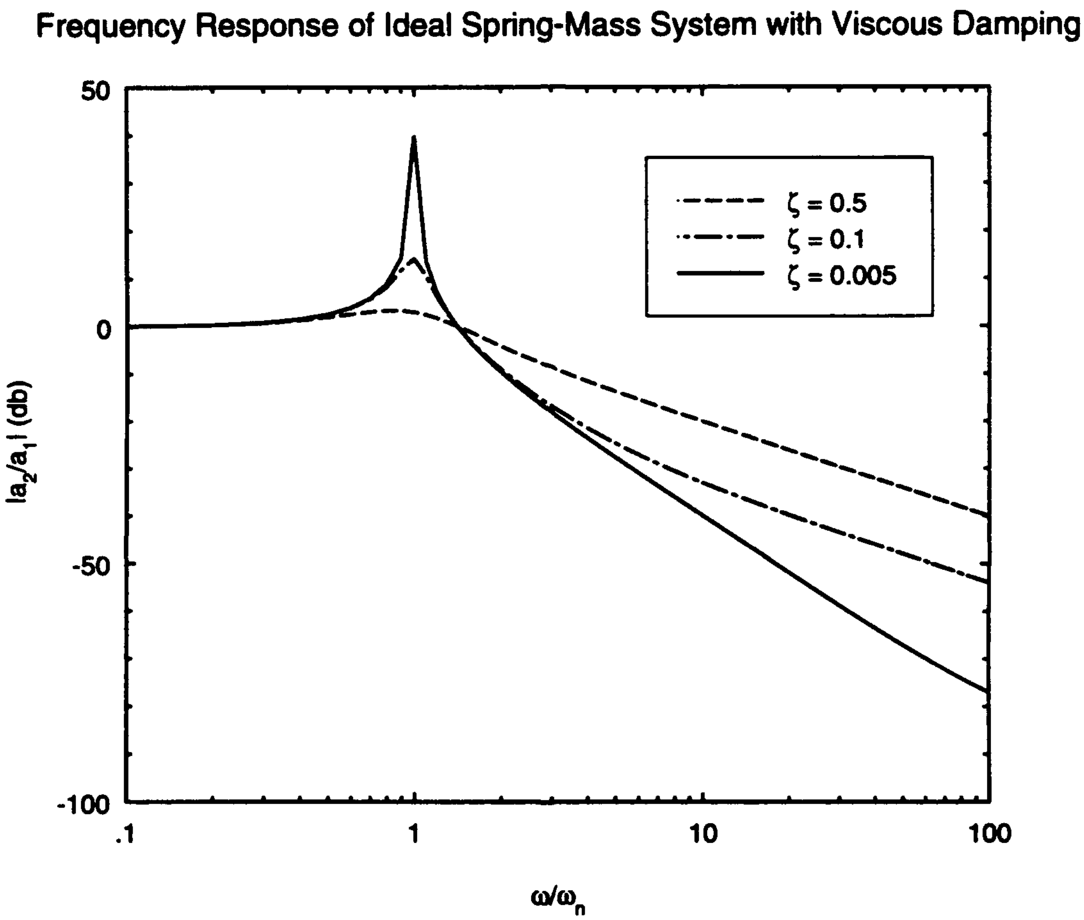

Fig. 3 Vibration Response Using a Lumped Parameter Analysis

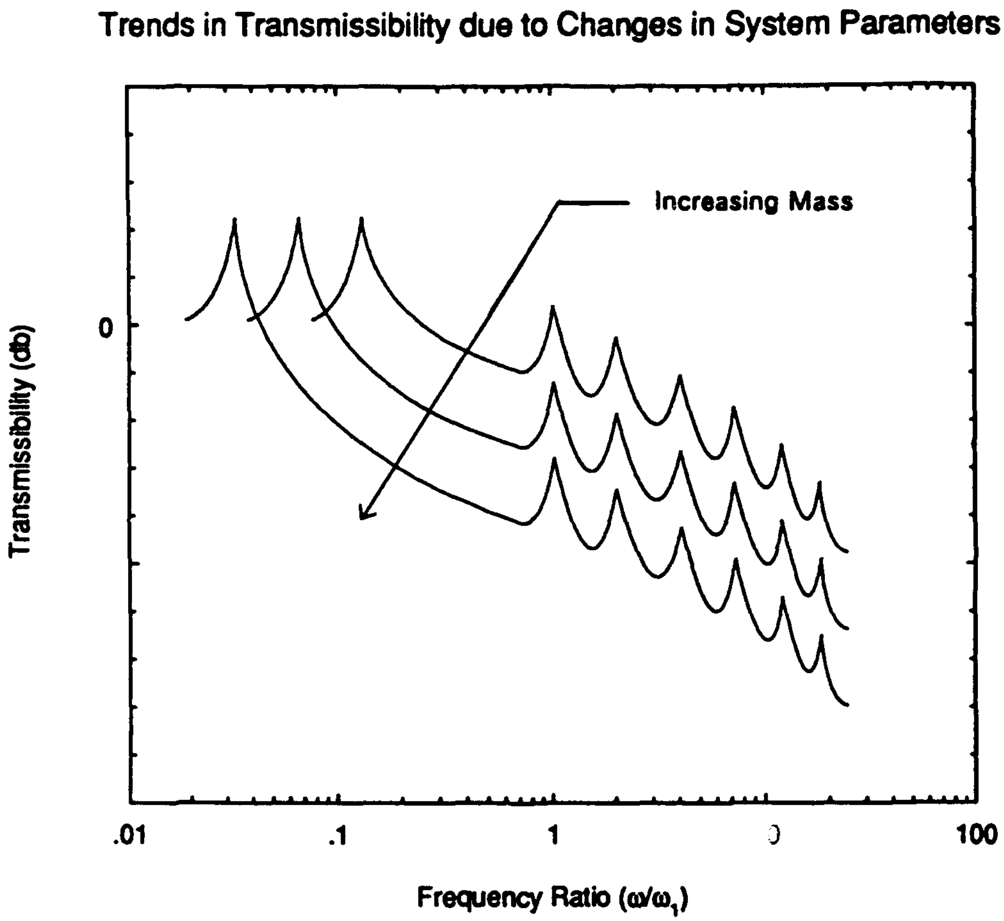

Fig. 4 Changes in the Transmissibility Curve as the Result of Changing Mass

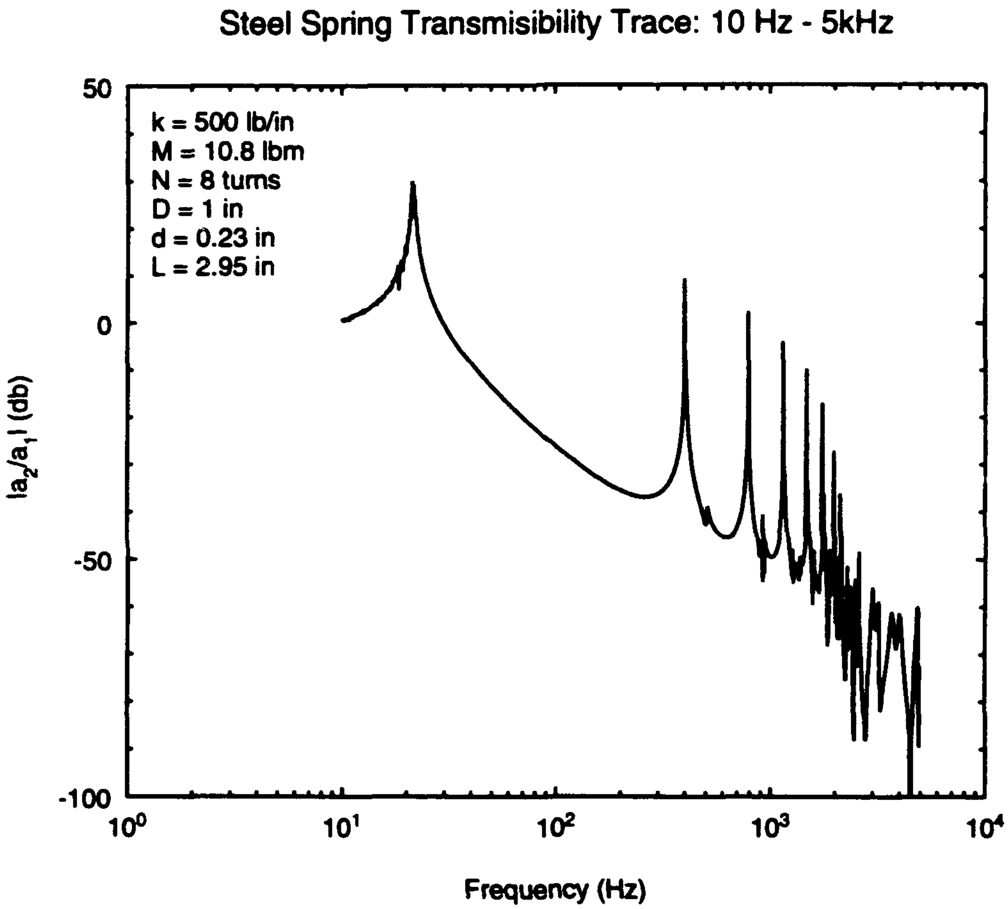

Fig. 5 Transmissibility of a Steel Spring

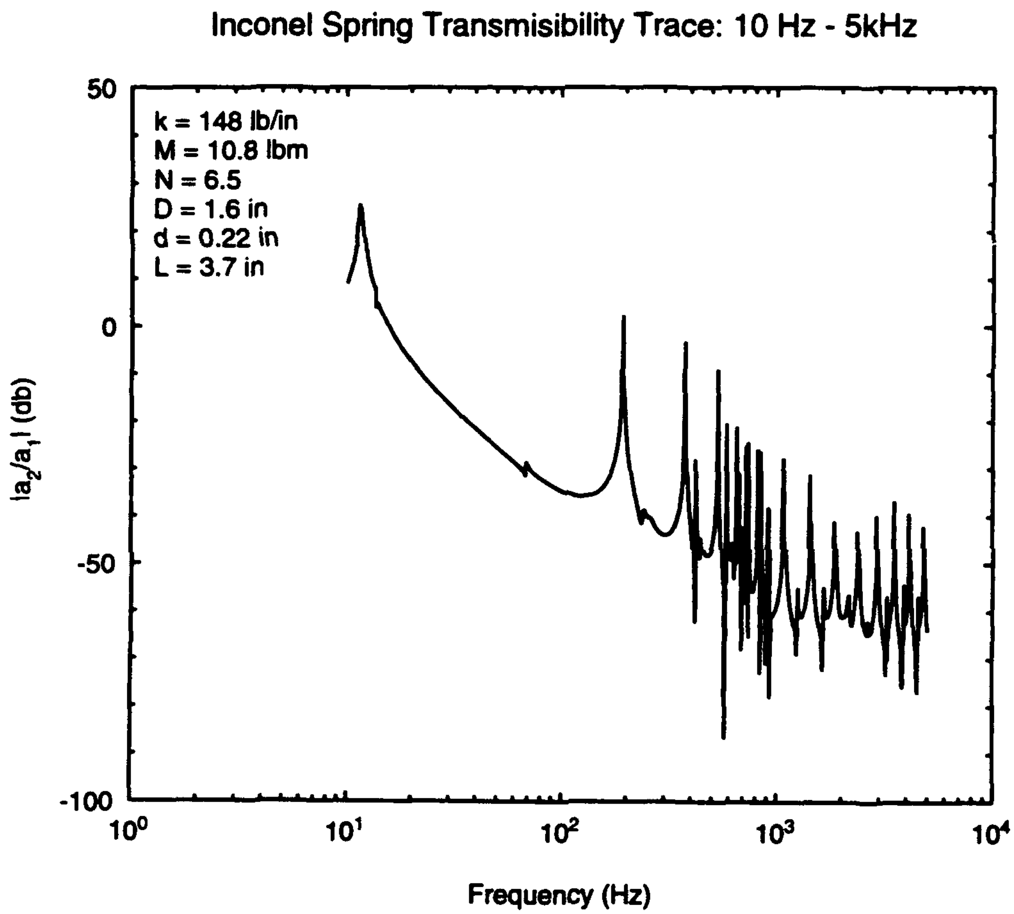

Fig. 6 Transmissibility of an Inconel Spring

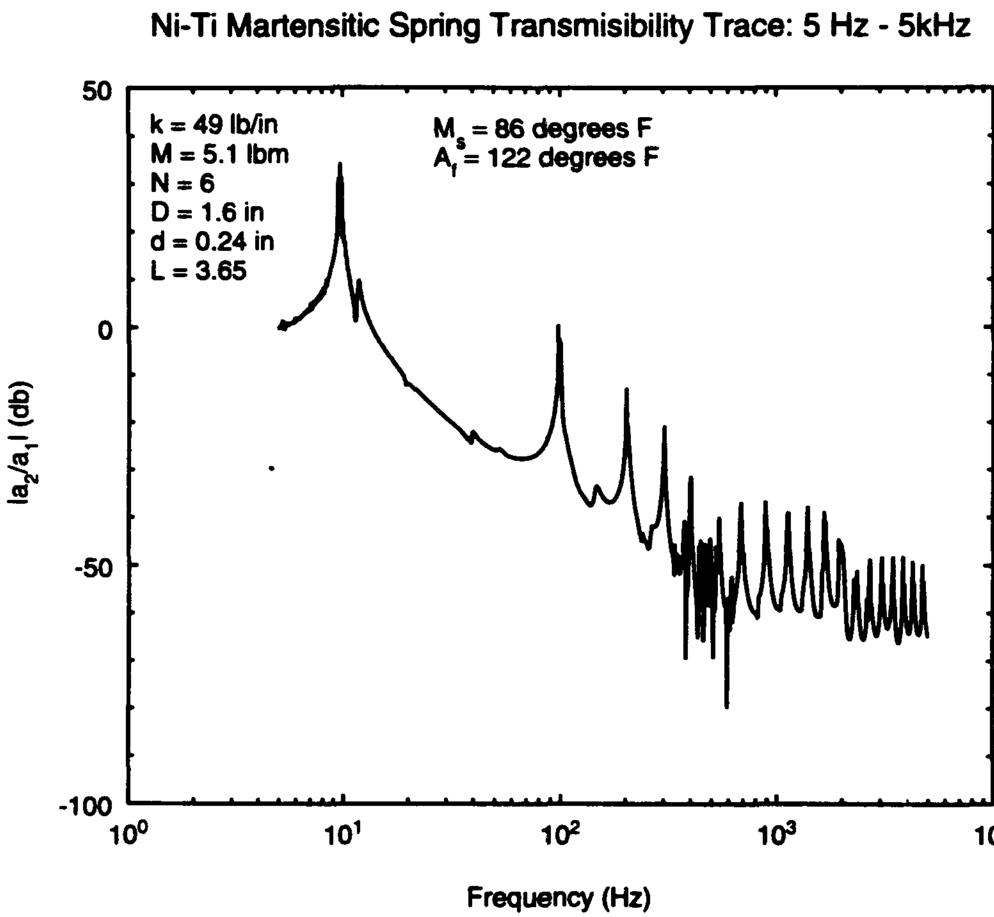

Fig. 7 Transmissibility of a Ni-Ti Spring in the Martensitic Condition

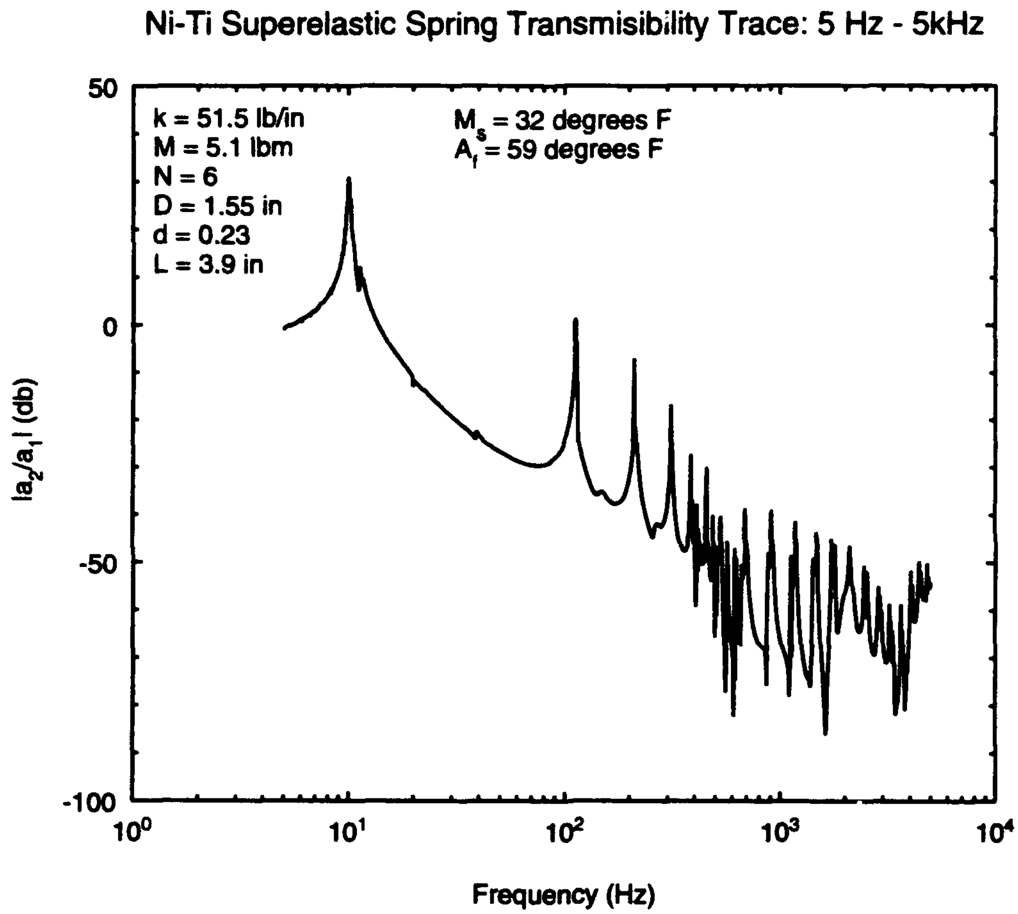

Fig. 8 Transmissibility of a Ni-Ti Spring in the Superelastic Condition

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