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Dr. Kenneth A. Cunefare

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The Georgia Institute of Technology, Woodruff School of Mechanical Engineering
Atlanta, GA 30332-0405

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13. ABSTRACT (Maximum 200 words)

This project investigated a novel variation on the concept of a tuned vibration absorber or damper: the State-Switched Absorber (SSA). The SSA is capable of altering its stiffness state nearly instantaneously. The change in stiffness causes a change in the resonance frequencies of the system, thereby instantaneously 'retuning' the SSA to a new frequency. The state-switching technique increases the effective bandwidth of the absorber, can be made to be effective against multiple frequencies within its bandwidth, and, in addition, holds forth the potential for unique applications, such as the preferential "pumping" of energy into the absorber. The project yielded modeling methods for the absorber applied to common structural elements, e.g., beams and plates; switching rules for actuators; analysis methods for placement and optimization; SSA prototypes; control circuit implementations, and experimental validation of state-switched absorbers

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Problem Studied

This project addressed by this report investigated a novel variation on the concept of a tuned vibration absorber or damper: the State-Switched Absorber (SSA). The SSA is capable of altering its stiffness state nearly instantaneously. The change in stiffness causes a change in the resonance frequencies of the system, thereby instantaneously 'retuning' the SSA to a new frequency. The state-switching technique increases the effective bandwidth of the absorber, can be made to be effective against multiple frequencies within its bandwidth, and, in addition, holds forth the potential for unique applications, such as the preferential "pumping" of energy into the absorber.

The project investigated:

1) Development of modeling methods for the absorber applied to common structural elements, e.g., beams and plates.
2) Development of switching rules for actuators
3) Development of analysis methods for placement and optimization
4) Development of design rules and SSA prototypes
5) Control circuit development
6) Experimental examination of state-switched absorbers

Summary Results

The following briefly summarizes the technical developments achieved during the course of the project, and available in archival and conference publications. Key results include the development of effective simulation tools, theoretical and experimental validation of the control concept, and, development of prototype concepts.

Simulation code was developed for a variety of dynamical systems, forcing excitations, and state-switching rules. The capability now exists to simulate state-switched absorbers applied to single degree of freedom, two degree of freedom, beam, and plate systems. For the beam and plate systems, the ability to consider point and distributed excitation, or both combined, were implemented. Simulation code to permit analysis of time-varying and random disturbances, eliminating the limitation of considering combinations of simple harmonic excitations, was also developed. Several switching control algorithms, including algorithms based on the objectives of maximum energy extraction, frequency time-sharing, and purely random switching, were implemented and evaluated. The maximum-work-extraction logic routinely demonstrated the best performance over other logic schemes. In all cases analyzed, state-switched vibrations absorbers perform in general significantly better than, and never worse than, passive vibration devices.

The simulation tools were used to perform a detailed study of the role that damping plays in the performance of the state-switched absorber. Considering a number of damping models, excitations, and systems, the damping conditions for which state-switching yields greater performance as compared to passive absorbers with equivalent damping were determined. The performance benefits of the absorber were determined to be insensitive to the particular damping model employed in the simulations. This increased the confidence in the robustness of the concept.

The predicted theoretical performance of the state-switched absorber was confirmed experimentally. A dynamic analog of the state-switched absorber applied to a base mass was constructed, comprising a 2-degree-of-freedom state-switched vibration absorber system based on a switchable magneto-rheological clamping device. The state-switching control of this system was implemented using a digital signal processing system. Trials clearly demonstrated that the state-switched vibration absorber was capable of reducing the base motion of a two-degree of freedom system subjected to multiple harmonic forces to a greater extent than a passive vibration absorber.

In addition, a single-degree-of-freedom test system to validate analytical developments regarding energy absorption and optimal switch timing was been constructed. Results from this demonstrator indicate that the switch logic developed in this research has clear advantages over other switching logic schemes proposed elsewhere. The state-switching control logic employed in this work was proven through experiment to provide smooth, shock-free operation. Further, control schemes as implemented by others were experimentally demonstrated to have the potential to generate significant mechanical shocks, which may be undesirable.

Beyond the above results, documented in the published literature, significant results were achieved in the area of optimizing placement of SSA absorbers on extended structures, and, in the development of Magneto-Rheological-based SSA's. This material has not yet been published. The following addresses each of these results.

A state-switched absorber design was developed whose size, weight and operational frequency range is comparable to those used in commercial vibration suppression applications. The design employs a Magneto-Rheological (MR) elastomer. The magnetic coil required for stiffness actuation of the device is integrated as part of the moving mass of the absorber, representing a novel means of reducing the complexity of the overall system. Prototypes of the device have been constructed and tested, and demonstrate frequency shifts on the order of 460%. Appendix 1 provides a draft paper describing this concept in detail.

In concert with this MR absorber design, low-cost sensor and control systems for practical applications were developed in concept. The basic control logic only requires knowledge of the zero-deflection position of the absorber, and of the sign of the base and relative velocities. Since only the signs of the velocities are required the system does not need precise, calibrated measurement of these parameters. Low-cost optical sensors were determined to provide the means to detect the zero-deflection point, as well as the signs of the velocities.

With respect to placement optimization of SSAs on extended structures, a genetic algorithm was implemented. It was discovered that the kinetic energy results in SSA systems are discontinuous. Essentially, a small perturbation in some parameter in the SSA system, does not necessarily give a small perturbation in the kinetic energy metric. This discontinuity is due to change in the time response of the system, thus potentially

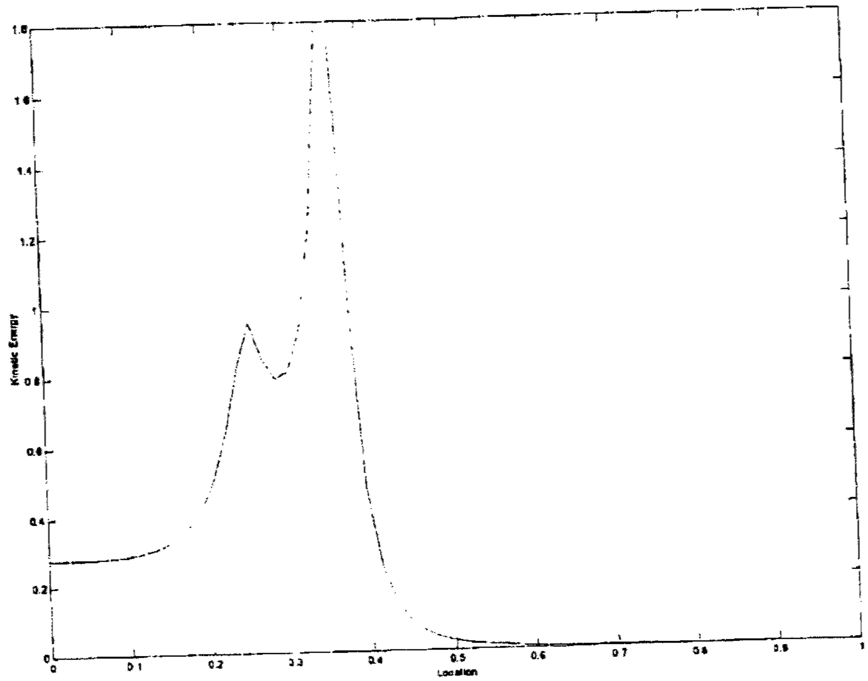

Figure 1: Kinetic Energy of the Base as a Function of Absorber Location With a Lower Tuning Frequency = 1.0226 and an Upper Tuning Frequency = 1.029

changing the occurrence of switch events. Even changing the occurrence of one switch event can cause large changes in the kinetic energy of the system. Because of this discontinuity, optimization is rather difficult through typical methods.

Work was done on basic optimization of a cantilevered beam forced at the center with two frequency component forcing. The parameters checked for optimization were absorber location and tuning frequencies. Figure 1 depicts the beam kinetic energy as a function of location along the beam for a constant set of tuning frequencies. As can be seen from Figure 1, the optimum location for a state-switched absorber is at the free end of a cantilevered beam. At this location the kinetic energy is at its lowest. It can also be seen in Figure 1 that there are locations at which the kinetic energy spikes and the SSA suppresses vibrations poorly.

A similar investigation was done with tuning frequencies. The absorber location was fixed at the free end of the cantilevered beam and the beam kinetic energy was determined for a range of tuning frequencies. The results of this investigation are shown in Figure 2. In this figure, the blue color corresponds to low kinetic energy in the beam and is desired; the red color corresponds to large kinetic energies and is to be avoided. As can be seen, the best performance occurs along the diagonal where the tuning frequencies are equal or close to being equal. When the tuning frequencies are equal, the

Figure 2: Kinetic Energy of the Base as a Function of SSA Tuning Frequencies With a Constant Location = 1

absorber acts as a passive tuned vibration absorber. From these preliminary results, there seems to be little advantage to state switching in the cantilevered beam system. Currently, work is being done to try to expand the range of tuning frequencies considered.

Publications and reports

Manuscripts published in peer-reviewed journals

Kenneth A. Cunefare, Sergio De Rosa, Nader Sadegh, Gregg Larson, "State switched absorber/damper for semi-active structural control," Journal of Intelligent Material Systems and Structures, Vol. 11(4), pp. 300-310, 2001.

Kenneth A. Cunefare, "State-switched absorber for vibration control of point-forced beams," Adaptive Structures and Materials Symposium special issue of the Journal of Intelligent Material Systems and Structures, 13(2), pp. 97-106, 2002. Also, presented at ASME IMECE 2000, November 5-10, Orlando, FL, AD Vol. 60, "Adaptive Structures and Material Systems – 2000," pp. 477-484.

Manuscripts submitted to peer-reviewed Journals, under review

Mark Holdhusen and Kenneth A. Cunefare, "Damping Effects on the State-Switched Absorber Used for Vibration Suppression," submitted to the Journal of Intelligent Material Systems and Structures, October 2001. Also, Proceedings of the SPIE Smart Structures and Materials Symposium, Newport Beach, CA, April, 2001, paper 4326-26.

Mark Holdhusen and Kenneth A. Cunefare, "Experimental vibration control of a two-degree-of-freedom state switched absorber system," submitted to the ASME Journal of Vibration and Acoustics, 2002. Also, presented at ASME IMECE 2002, November 17-22, New Orleans, LA, paper IMECE2022-33555.

Gregg D. Larson and Kenneth A. Cunefare, "Experimental investigation of control logic for State-switched dampers," submitted for review, Journal of Vibration and Acoustics, November, 2001. Also, presented at the 18th ASME Biennial Conference on Mechanical Vibration and Noise, Pittsburgh, PA, September 9-12, 2001. 18th ASME Biennial Conference on Mechanical Vibration and Noise, Active and Hybrid Controls, paper DETC2001/VIB-2146, Pittsburgh, PA, September 9-12, 2001

Manuscripts submitted, not published

Kenneth A. Cunefare, "State-switched absorber for semi-active control of plates," submitted for review, AIAA Journal of Aircraft, May, 2001. Also, presented as paper AIAA 2001-1562 at AIAA SDM Conference, Seattle, WA April 16-19, 2001.

Manuscripts submitted to conferences with proceedings

Anne-Marie Albanses and Kenneth A. Cunefare, "Properties of a magnetorheological semiactive vibration absorber," submitted for SPIE Smart Structures and Materials Symposium, San Diego, CA, 2003.

Papers presented at conferences, no proceedings

Kenneth A. Cunefare, "State-switching as a semi-active approach to vibration control," 4th NASA AST Interior Noise Workshop, Feb. 15-17, 2000, Hampton, VA.

Kenneth A. Cunefare, "State-switched absorber for control of beams," 139th Meeting of the Acoustical Society of America, May 30-June 3, 2000, Atlanta, GA.

Mark Holdhusen and Kenneth A. Cunefare, "Experimental validation of the State-Switched Absorber for two-component harmonic forcing," 141st Meeting of the Acoustical Society of America, 4-8 June, 2001, Chicago, IL. Journal of the Acoustical Society of America, 109(5), Pt. 2, pp. 2351(A).

Anne-Marie Albanese and Kenneth A. Cunefare, "The analysis of a state-switched absorber design concept," 144th Meeting of the Acoustical Society of America, 2-6

December, Cancun Mexico. Journal of the Acoustical Society of America, 112(5), Pt. 2, pp. 2348(A).

Scientific personnel

Dr. Gregg Larson (Research Engineer)

Mr. Mark Holdhusen (Graduate Student). Has received MS degree, has passed PhD qualifying examination.

Ms. Anne-Marie Albanese (Graduate Student) Completing MS degree, has passed PhD qualifying examination (Anne-Marie was supported principally by an NSF Fellowship. She conducted research into alternative state-switching concepts than those covered by the ARO scope).

Report of Inventions

"State-Switched Absorber," Invention Disclosure to the GT Office of Technology Licensing, April, 2000. Kenneth A. Cunefare, Gregg Larson, James Martin, Co-Inventors.

"Tunable adaptive vibration absorber employing magnetics with variable gap length," Invention Disclosure to the GT Office of Technology Licensing, December, 2002. Kenneth A. Cunefare, Anne-Marie Albanese, Co-Inventors.

Technology Transfer

Draft of a paper addressing state-switched vibration control was provided to Mr. Gareth Knowles of QorTek, Inc., at his request.

Contacts within the Ford Motor Company (Dr. John Ginder, Bill Schlotter). We benefited greatly in developing our in-house MR elastomer recipe through discussions with these individuals. In addition, as part of a larger presentation on brake squeal and vibration control research at Georgia Tech, Dr. Cunefare presented the state-switching concept to a full conference room at Ford's Science Laboratory on May 21, 2001.

Discussions with Mark Nichols and John Ginder of the Ford Motor Company related to the potential to integrate Ford's magneto- or electro-rheological elastomer technology into the project, and, to share with them the state-switching concept.

Discussion with Newport Corp. to integrate MR-elastomer-based vibration absorber into proprietary application, 2002.

Appendix 1

The Analysis of a State-Switched Absorber Design Concept

Anne-Marie Albanese, Kenneth A. Cunefare
The Georgia Institute of Technology

ABSTRACT

A tuned vibration absorber (TVA) is a spring-damper-mass system used in many industries for the suppression of a specific vibration frequency, and has application for the suppression of aircraft fuselage vibration. A state-switched absorber (SSA) is similar to a TVA, except that one or more components in the SSA is able to instantaneously and discretely change properties, thus increasing the effective bandwidth of vibration suppression. In order to design a replacement SSA for the classic TVA, the SSA must operate in the appropriate frequency range, be lightweight and compact. An optimal SSA will also have a maximal frequency range that it can switch between. This paper discusses the development of a magnetorheological (MR) silicone gel used as the SSA switching element, the shape required to maintain a magnetic flux path, and the contribution of the magnet-mass to frequency shifting. The MR gel is iron-doped silicone, cured in the presence of a magnetic field. During operation, the applied magnetic flux is modified to change the natural frequency. The applied flux requirement forces the SSA to be a small ring. The SSA is designed to operate below 100 Hz.

1. INTRODUCTION

Tuned vibration absorbers (TVAs) are prevalent in many vibration control applications such as in aircraft fuselages due to their low cost and well-established vibration absorption capabilities. While active vibration controllers have been developed and offered in the market place for years, their use as vibration control mechanisms have been limited for several reasons. Active vibration controllers, while they can be highly effective, possess costly and highly sophisticated control algorithms. In addition, due to their real-time property-changing characteristics, an active vibration absorber subjected to an unanticipated excitation, or one that is improperly controlled, can actually add energy into the system and thus drive it into instability.

The semiactive absorber, referred to as a state-switching absorber or SSA in this paper, is a hybrid of the reliable TVA and the more effective active vibration controller. The SSA is capable of switching one or more of its properties, in this case its spring stiffness, but the control algorithm is fundamentally different from the active vibration absorber in that it only allows switching to occur at discrete times and to discrete states. In this way, the risk of adding energy to the system is eliminated since between states the SSA behaves as a classical, stable TVA.

Just because the SSA can control multiple vibration frequencies does not necessarily make it a TVA competitor. For the SSA to absorb vibration better than a TVA, the excitation source must be a variable-frequency one.[1] In addition, the SSA requires external energy to enable switching, both to the switching mechanism and to the sensors that feed into the control algorithm; this additional energy must be minimal. The SSA must be comparable in size and mass to the TVA; a large or bulky system will not do. It must also be able to operate within the same frequency range.

This paper will discuss the elements considered in designing an SSA. This includes a brief overview of state switching and magnetics, the size and shape of an SSA, the method of state switching employed, and the contribution of the mass-magnet to the stiffness change. Although control algorithms are an important aspect of the SSA, the control algorithm implemented is dependent upon the nature of the excitation, and is beyond the scope of this paper.

2. MAGNETICS: A REVIEW

The switching aspect of the SSA developed for this work is a magnetorheological (MR) silicone. The MR silicone consists of a two-part silicone with embedded iron particles aligned in chains, as seen below in figure 1. When a magnetic flux path flows through this composite material, the magnetic forces will oppose any displacement the iron particles experience away from their magnetic equilibrium point. This causes the effective stiffness of the silicone to increase.[2]

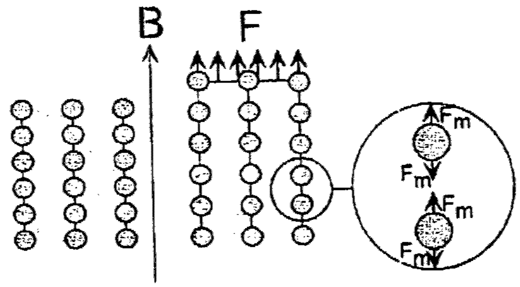

Figure 1: A MR silicone subjected to a magnetic flux B and tensile force F induces intermolecular forces F_m.

The force follows the inverse square law, as described below in equation (2.1) as

$$\check{F}_m = \frac{\alpha_m}{r^2}, \tag{2.1}$$

where $\check{F}_m$ is the attractive force from each iron particle, r is the distance between each particle, and α_m is a constant to be determined. While the particle-to-particle attraction yields a stiffness change, the primary change in stiffness is going to be due to the large iron core halves. The attractive force of two magnet ends together, or in this case, two ends of the horseshoe-shaped iron halves, can be described as equation (2.2),

$$F = \frac{\mu_0}{4\pi r^2} mm', \tag{2.2}$$

where m and m' are the magnet strengths of each attracting pole, related to magnetic flux B by $B = \frac{\mu_0 m}{4\pi r^2}$, r is the distance between each pole, and $\mu_0 = 4\pi \times 10^{-7}$ is the magnetic permeability. For our setup, m and m' are equal and opposite, so that equation (2.2) becomes

$$F = \frac{-\mu_0 m^2}{4\pi r^2}. \tag{2.3}$$

In designing our SSA, we wanted to have a maximum change in the magnetic strength. Since magnetic strength is related to magnetic flux B, we designed our coil to be able to magnetically saturate the composite. A description of equations (2.4) and (2.5) can be found in a tutorial by Magnetic Products and Services, Inc. [3] A line of current produces flux, but a coil of wires carrying a current of I Amperes generates B Gauss of flux through the center of the coil according to equation (2.4)

$$B = \frac{0.49 N \cdot I}{\sqrt{s^2 + 4r^2}}, \tag{2.4}$$

where s is the length of the coil in inches and r is the radius of the coil. Magnetic flux can be amplified if it travels around a steel loop with a small air gap of size l, in inches, whose relationship to current is found in equation (2.5)

$$B = \frac{0.49 \cdot 10^{-5} \cdot N \cdot I}{l}. \tag{2.5}$$

B describes the magnetic flux density through the steel coil. The Lord Corporation found that the flux density through a MR fluid, B_{SSA}, is

$$B_{SSA} = \frac{B_{st} \cdot A_{st}}{A'_{SSA}}, \tag{2.6}$$

where $A'_{SSA} = \pi\left(r + \frac{l}{2}\right)^2$, or the effective pole area, and $B_{st} = B =$ flux density going through the steel coil.[4]

3. STATE SWITCHING: AN OVERVIEW

The SSA is permitted to switch only at discrete times and to discrete states. Between switches, the SSA behaves as a classic TVA at its j[th] state, as shown in figure 2.

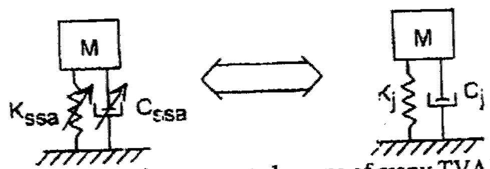

Figure 2: An SSA, on left, represented as one of many TVA's, on right.

The effectiveness of an SSA over a TVA lies in its control algorithm. Although not a control algorithm in and of itself, it has been determined that limiting switch cases to that when the force across the switched element is zero eliminates transients that would transfer energy from the old state to the new.[5] Control algorithms dictate at which possible switch points the SSA should switch to give greater vibration absorption than the TVA.

The state-switched absorber examined in this work is effectively a toroid with a small air gap, as seen in figure 3. The silicone composite in the air gap behaves as a switchable spring with losses, modeled as light damping.

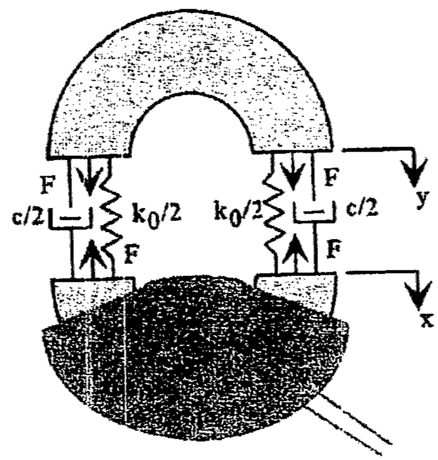

Figure 3: Schematic of an MR SSA.

When no current runs through the wires, the spring constant has some value k_0 the equation of motion is

$$m\ddot{x} + c\dot{x} + k_0 x = c\dot{y} + k_0 y. \tag{2.7}$$

The displacement values x and y describe the absorber and base displacement, respectively, as depicted above in figure 3.

As discussed in the previous section, the magnetic flux caused a particle-to-particle attraction between the iron particles within the silicone composite itself. However, the primary cause of the stiffness change was due to the magnetic poles on the large iron mass pieces themselves. From equation (2.3), the value r is the relative displacement between x and y, or $r = x - y$. Since x and y consist of small deviations about some mean displacement, $r = (x_0 + x) - (y_0 + y) = (x_0 - y_0) + (x - y)$, where x_0

and y_0 are mean displacements. Assuming small deviations x and y, equation (2.3) becomes equation below.

$$F = \frac{\mu_0 m_j^2}{4\pi\Delta_j^2}\left[-1 + \frac{2}{\Delta_j^2}(x-y)\right], \tag{2.8}$$

where $\Delta_j = x_{0j} - y_{0j}$, the j[th] state's static displacement. Substituting into equation (2.7) and rearranging, we find that the differential equation for the fluxed case becomes equation (2.9), below.

$$m\ddot{x} + c\dot{x} + \left(k_0 + \frac{\mu_0 m_j^2}{\pi\Delta_j^3}\right)x = c\dot{y} + \left(k_0 + \frac{\mu_0 m_j^2}{\pi\Delta_j^3}\right)y + \frac{\mu_0 m_j^2}{2\pi\Delta_j^2}. \tag{2.9}$$

We see that the net spring constant becomes

$$k_{eq} = \begin{cases} k_0 & for\, B = 0 \\ k_0 + \dfrac{\mu_0 m_j^2}{\pi\Delta_j^2} & else \end{cases}. \tag{2.10}$$

The other effect can be seen in the right-hand side of equation (2.9). The forcing constant means that the silicone will be forced to displace statically. If gravity is neglected, one can see that the static displacement is in fact a function of the magnetic strength, m_j.

$$\Delta_j^{st} = \left(\frac{-3\mu_0 m_j^2}{4\pi k_0}\right)^{1/3}. \tag{2.11}$$

This implies that the magnetic strength forces the composite to statically compress.

4. PHYSICAL DESIGN CONSIDERATIONS

A MR silicone of length l whose stiffness change is directly proportional to the magnetic flux that runs through it should have a maximum flux change for the least amount of power input. Therefore, two MR silicones can be placed in parallel as seen below in figure 4, producing two small gaps in a steel loop.

The coil must be able to fit inside the steel without constraining the MR silicone motion. This requirement is satisfied by adhering to (3.1) below:

$$N \le \frac{A_{SSA}}{A_{wire}} = \left(\frac{r_{av} - \frac{s}{2}}{r_{wire}}\right)^2, \tag{3.1}$$

where N is the number of coils, r_{av} is the average of the inner and outer radii for the SSA, s is the length a side of the steel coil, and r_{wire} is the radius of the magnet wire. The wire thickness must be chosen such that it can carry the maximum current load necessary and still satisfy equation (3.1).

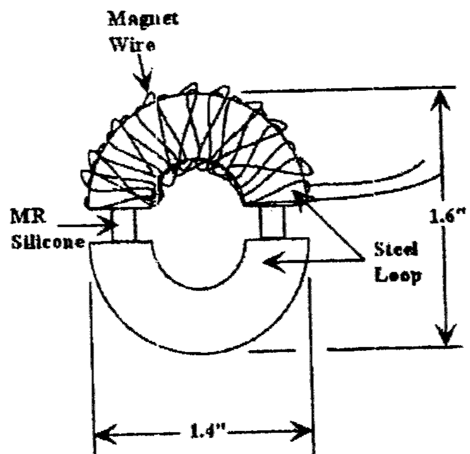

Figure 4: Final design for the SSA.

We wished to have an SSA with natural frequencies below the 100 Hz mark, but with a maximum natural frequency change between the unfluxed and maximally fluxed cases. The spring constant was presumed to be $k_{SSA} \propto \frac{E_{SSA}A}{L}$. Therefore, the spring stiffness change was modeled as an elastic modulus change. In addition, we wanted an SSA that had no dimension larger than 3", and it should have a mass of less than 100 g. The end design can be seen in figure 4.

5. EQUIPMENT

A two-part silicone was mixed thoroughly with iron microparticles and then cured in the presence of a magnetic flux. The silicone in question was a GE Silicone RTV6186, and the iron was from ISP Technologies by the name of R1430. The silicone was cured to roughly 150° F for 90 minutes in the presence of a magnetic flux to align the iron particles. The power supply used to drive current through the magnet coil was a KEPCO BOP36-6D. A low-carbon steel was used to construct the steel loop. The test setup can be seen below in figure 5. Siglab model 50-21 provided a random noise source, bandlimited to 1000 Hz. It was amplified by an LDS PA25E power amplifier, and then actuated by an LDS shaker, model v2.0.3. Data from the accelerometers, Kistler model 866 C5, were powered by a Kistler power supply model 5134, collected by Siglab, and then exported to a PC.

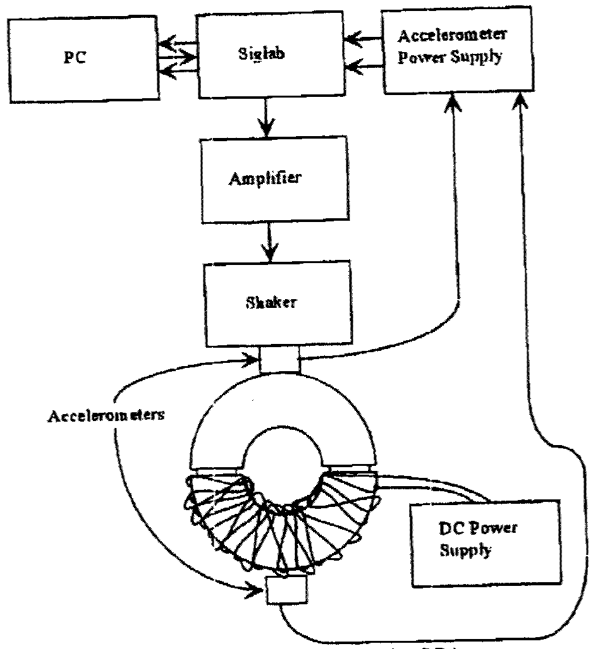

Figure 5: Test setup for the SSA.

6. PROCEDURES

Silicone was prepared by mixing the desired percent iron (R1430) to part B of the two-part silicone mixture. Then an equal mass part A was added to the mixture. Silicone was mixed for ten minutes on a hot plate heated to 50°C (122°F). The silicone mixture was then cured for 30 minutes at an elevated temperature under 4.5 A current. The silicone sample produced was cylindrical with a 0.15" radius and 0.2" in length.

Once cured, the sample was cut in half length-wise and each half was secured to the iron halves using Loctite 454 epoxy. Siglab was used to produce broadband white noise, delivered to the base mass via the shaker. The accelerometers measured the acceleration of both the base and absorber mass which were then recorded.

7. RESULTS

It was found that better than a 5:1 maximum to minimum natural frequency ratio could be achieved in the 30-35% iron by volume range, as shown in figure 6. This graph is somewhat misleading, though, because even a 0% iron induces a frequency change. However, this is not an increasing natural frequency with increasing coil current. Figure 7 shows that the natural frequency in fact decreases with increasing current.

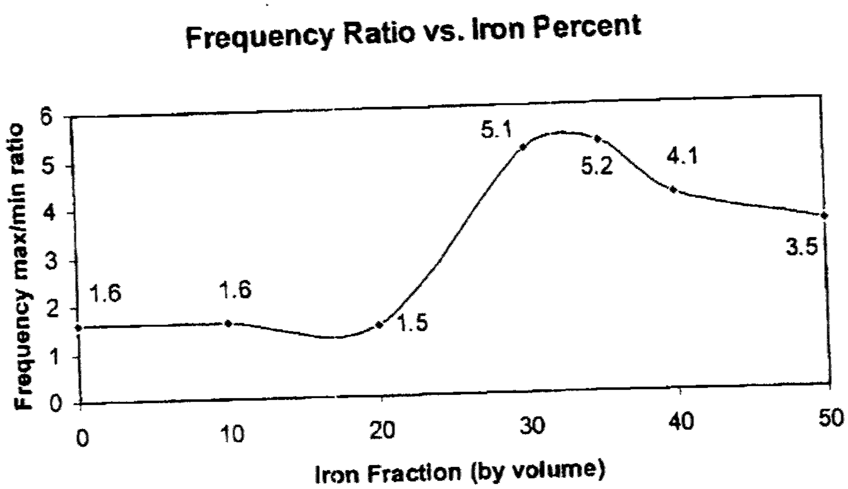

Figure 6: Frequency change ratio for different iron fractions

One can also observe in figure 7 that there are different spring stiffnesses for the 0 A value. This is because the elasticity of a material increases when particle fillers are included.[6, 7] All materials with 30% iron and below have identical initial stiffnesses because talc powder was added to obtain a 30% particle composition by volume to enhance the material strength.

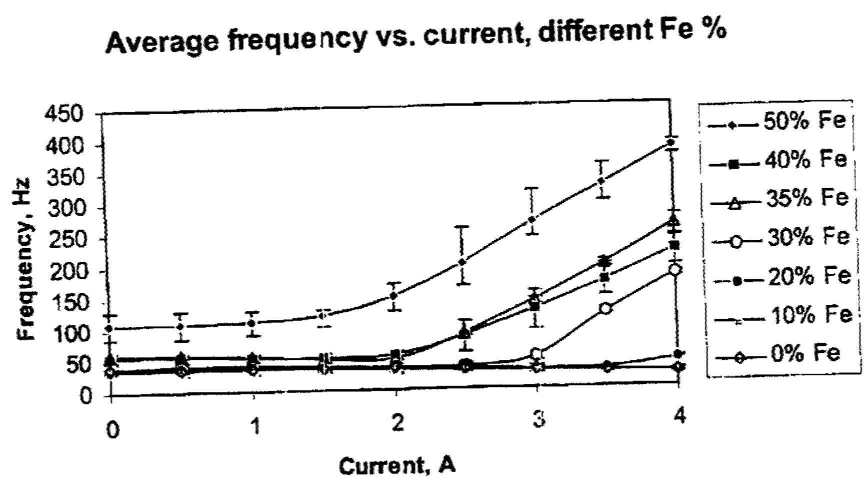

Figure 7: Natural frequencies for different iron fractions at various current levels.

8. CONCLUSION

It has been demonstrated in this paper that a MR silicone can be used as a state-switching spring in an absorber to produce up to a 5:1 natural frequency change. The design is iron-percentage dependent, and the best iron percent was determined to be around 35% iron fraction by volume. Within this design, the absorber mass is too big for pure silicone to support; talc powder was added to strengthen the silicone when not enough iron powder would otherwise be present, i.e., for small percentages of iron. Otherwise, the iron powder provides strengthening for the silicone and a means for magnetic flux to pass through what would otherwise be effectively an air gap. This design is small and compact; the largest length dimension is 4 cm, and the whole device weighs less than 100 g.

9. REFERENCES

1. Cunefare, K.A., *et al.*, *State-switched absorber for vibration control.* Journal of Intelligent Material Systems and Structures (accepted for publication), 2000.
2. Ginder, J.M.S., W. F.; Nichols, M. E., *Magnetorheological elastomers in tunable vibration absorbers.* SPIE Smart Structures 2001, 2001.
3. Nippes, P.I., *Principles of Magnetism and Stray Currents in Rotating Machinery*, . 2001, Magnetic Products and Services, Inc.
4. Lord Corporation, M.D., *Magnetic Circuit Design*, . 2001, Lord Corporation.
5. Cunefare, K.A.S., Nader; Larson, Gregg, *Fundamental Investigations of State-Switched Vibration Control.* .
6. Guth, E., *Theory of filler reinforcement.* Journal of Applied Physics, 1945. **16**(20): p. 20-25.
7. Davis, L.C., *Model of magnetorheological elastomers.* Journal of Applied Physics., 1999. **85**(6): p. 3348-3351.