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Evaluation of Magnetostrictive Shunt Damper Performance Using Iron (Fe)-Gallium (Ga) Alloy

by Andrew James Murray and Dr. JinHyeong Yoo

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14. ABSTRACT

Structural vibrations can be controlled by active or passive methods. Active control uses sensors and actuators, and requires controls. Passive control methods gradually reduce vibration by dissipating energy through dampers including rubber, hydraulic dashpots, or friction. Magnetostrictive materials (iron [Fe]-gallium [Ga] alloy, for example) can be used in passive structural vibration damper elements. Magnetostrictive materials are distinguished by the phenomenon of dimensional changes occurring in response to a change in the magnetization of ferromagnetic material. The inverse is also true, whereby magnetization occurs in response to changes in applied stress fields. The magnetostrictive material can harvest electricity out of structural vibrations. To dissipate the electrical energy from the energy harvester configuration, a shunt, or a load, is attached. With careful tuning the shunt can increase the efficiency of the magnetostrictive damper. The ideal levels of resistance and capacitance in the shunt are investigated to maximize the shunt damper performance. Comparisons to the effectiveness of piezoelectric shunt dampers are discussed.

15. SUBJECT TERMS

Magnetostrictive materials, iron-gallium (Fe-Ga) alloy, shunt damper

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Student Bio

Andrew Murray is currently an undergraduate student at the Pennsylvania State University. He is a junior in the mechanical engineering program. He is deliberating if graduate school is right for him. He has never taken vibrations or signal processing so most everything in this report was brand new to him at the beginning of the summer.

1. Introduction/Background

Structural vibrations are an extensive problem throughout many fields of study. From vibrating circuits in computers to earthquakes, we are constantly encountering vibrations and their consequences. Vibrations can lead to discomfort, damage structures, reduce the efficiency of a process, and lead to many more negative consequences. Vibrations can lead to further damage when a structure is vibrating at its natural, or resonant, frequency. For these reasons, the study of vibration control and damping is always relevant.

Vibrations are inherently part of any structure that contains moving parts. Many methods are used to decrease or dampen vibrations. The methods can be categorized into two main categories: active control methods and passive control methods. Active control methods use sensors and actuators, and require controls. Often, they require power to be input as well as careful tuning and upkeep. However, active control methods can be quite robust and effective over certain frequencies and structural modes. Active control tends to be costly yet very effective. On the other hand, passive control methods gradually reduce vibration by dissipating energy through dampers such as rubber, hydraulic dashpots, or friction. Passive control methods tend to be less robust but are easier to implement and need less maintenance and tuning than active control methods. Passive control methods may not be as effective as active control, but they can be significantly less expensive.

Magnetostrictive materials (iron [Fe]-gallium [Ga] alloy, for example) can be used in passive structural vibration damper elements. Magnetostrictive materials are distinguished by the phenomenon of dimensional changes occurring in response to a change in the magnetization of ferromagnetic material (*1*). The inverse is also true, whereby magnetization occurs in response to changes in applied stress fields. This is called the Villari effect. The magnetostrictive material can harvest electricity out of structural vibrations. To dissipate the electrical energy from the energy harvester configuration, a shunt, or a load, is attached.

The magnetostrictive energy harvester has two main parts: the Fe-Ga unimorph beam and the pickup coil (figure 1). The Fe-Ga beam is attached to the underside of a brass beam. Brass is used because it is not magnetic. Permanent magnets are attached to each end of the beam to generate a uniform magnetic field through the beam. When the beam vibrates, the magnetostrictive strip oscillates between tension and compression. As this oscillation occurs, the Fe-Ga beam's magnetic field oscillates as a result of magnetostriction. The oscillating magnetic field creates a change in the current through the pickup coil. This creates a potential difference across the ends of the coil according to Faraday's law. The shunt is attached to the ends of the pickup coil to create a circuit. There are brass protective holders for the magnets at each end of the beam and around the pickup coil. The weight of magnet holders at the end of the beam can control the beam's resonant frequency. The only magnetic elements are the magnetostrictive strip and the permanent magnets at either end. Figure 1 shows a conceptual diagram of the system and figure 2 shows the actual system used in this study. The load cell underneath of the system measures the input force to the system and is used as a reference signal for the transfer function calculation.

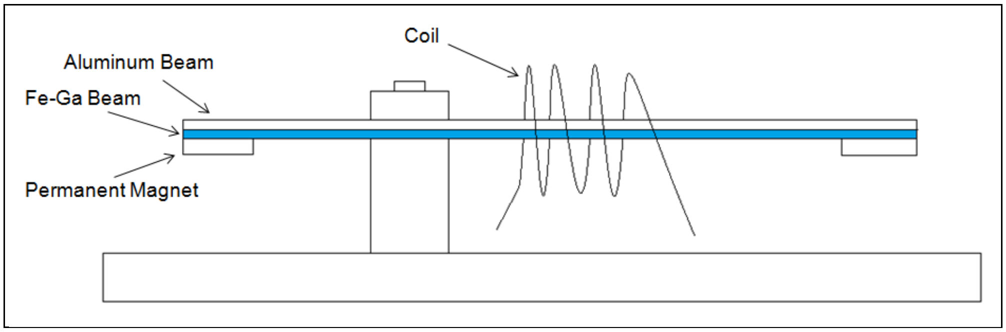

Figure 1. Diagram of energy harvester.

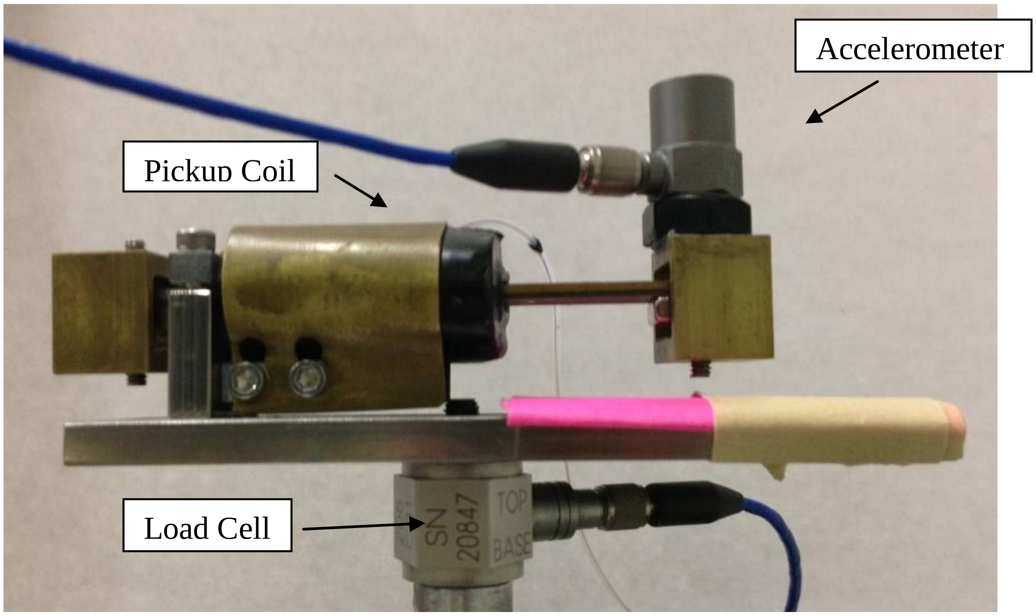

Figure 2. Energy harvester.

The inspiration for magnetic shunt dampers stems from the research in piezoelectric shunt dampers (*2*). Piezoelectric materials are distinguished by the phenomenon of dimensional changes occurring in response to changes in the electrical charge. The opposite effect exists as well, whereby changes in electrical charge occur in response to changes in applied stress fields. Because piezoelectric materials convert stress and strain directly to electricity, there is no need for a pickup coil to harvest the energy, as is needed in a magnetostrictive energy harvester. However, the magnetostrictive material, the Fe-Ga alloy, is machineable and weldable, and has a significant tensile strength, ~500 MPa. These characteristics make it possible to design robust structural bending resonant vibrators, which take advantage of the Fe-Ga alloy, which can endure both compressive and tensile stresses.

The shunt can be composed of a resistor, a capacitor, or a combination of the two. The resistor dissipates the electrical energy from the circuit. The dissipated energy is released into the surroundings as heat. The capacitor changes the phase of the current running through the circuit. The change in phase does not increase or decrease the dissipation of the energy. Instead, it manipulates how the magnetostrictive material's eddy currents affect the vibration. Eddy currents are circular electrical currents induced in a conductor within a changing magnetic field (*3*). As any current, eddy currents create their own magnetic field, which opposes the changing external magnetic field according to Lenz's Law (*4*). The capacitor changes the phase of the current through the shunt in a way that affects the eddy currents in the magnetostrictive material, figure 3. The green sinusoid represents voltage from the pickup coil and the blue sinusoid represents acceleration from the accelerometer. The right-hand sides plot of figure 3 shows the result when the capacitor is tuned to have a higher damping effect. The accelerometer and pickup coil can be seen in figure 2.

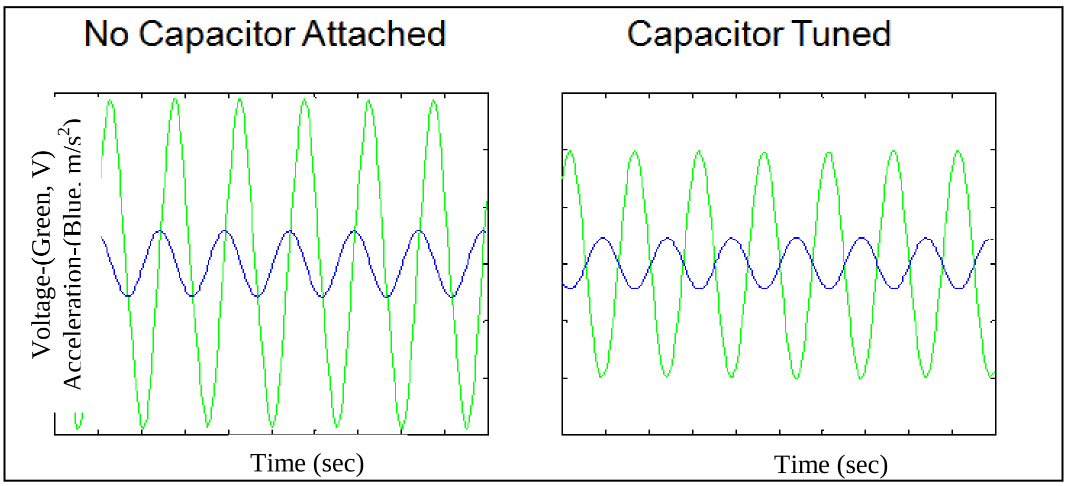

Figure 3. Voltage and acceleration response from experiment.

The effect of the capacitor is unique to magnetostrictive energy harvesters. In a piezoelectric energy harvester, no magnetic fields are present so there are no eddy current effects.

2. Experiment/Calculations

To determine the damping effectiveness of the shunt, the frequency response function (FRF) of the load input to the system and the beam's acceleration response was measured (*5*). The FRF was then used to determine the damping ratio, which is a sufficient representation of the damping effectiveness. This experiment was conducted over a wide range of capacitance and resistance values. The structure was modeled as a single degree of freedom vibrating system.

Our specimen is a cantilevered beam, which can be modeled by (*6*)

$$m\ddot{x} + c\dot{x} + kx = F \sin \Omega t, \tag{1}$$

where m, c, k, F, and Ω are the mass, damping coefficient, spring constant, amplitude of external force, and frequency of external force, respectively. The damping coefficient is the system's dissipation element, which decreases the displacement response of the system. The damping coefficient includes every form of damping from the inherent damping of the material to the applied damping of the magnetostrictive shunt damper. The roots of equation 1's characteristic equation are

$$\lambda_r = -\Omega_r \zeta_r \pm j\Omega_r \sqrt{1 - {\zeta_r}^2} \tag{2}$$

$$\Omega_r = \sqrt{\frac{k}{m}} \tag{3}$$

$$\zeta_r = \frac{c}{2\sqrt{km}} \tag{4}$$

where Ω_r and ζ_r are the undamped natural frequency and the damping ratio, respectively. The damping ratio is proportional to the damping coefficient and is an accurate measure of the overall damping of the system.

The FRF is the Laplace transform of the output divided by the Laplace transform of the input over a range of frequencies (*5*). The input is an external force and the output is the resulting acceleration. To acquire the FRF, a dynamic signal analyzer, which runs the fast Fourier transform, is used. The signal analyzer can then curve fit the FRF to find a pole in the Laplace frequency domain. This pole will be equal to equation 2. The formula, derived from equation 2, to determine the damping ratio from this pole is

$$\zeta_r = \sqrt{\frac{1}{\left(\frac{Im}{Re}\right)^2 + 1}} \tag{5}$$

where *Re* refers to the real part of the pole and *Im* refers to the imaginary part of the pole. This pole is located on the frequency response function at the peak around 65 Hz, as seen in figure 4. This is the resonant frequency of the structure. The acceleration increases dramatically at this point. The damping will be seen primarily at this point as the pointed peak will show more of a rounded top.

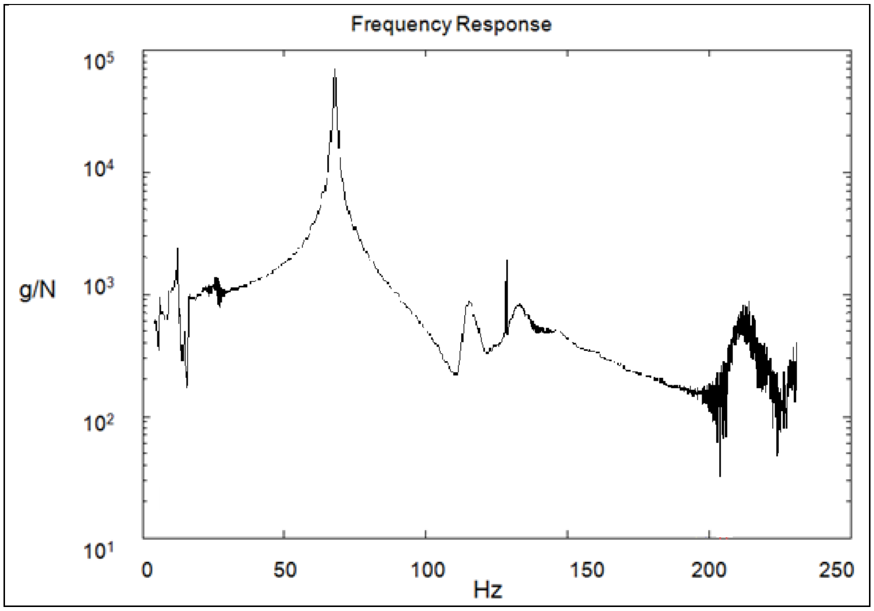

Figure 4. Frequency response without shunt.

Figure 5 shows the test configuration of the experiment. A HP 35670A digital signal analyzer is used as both the function generator and the signal analyzer. Labworks pa-138 and et-139 are used as the power amplifier and the electromagnetic shaker, respectively. The electromagnetic shaker applies the excitation force. A PCB 208C01 load cell measures the force input and a PCB 352C33 accelerometer measures the acceleration output, as seen in figure 2.

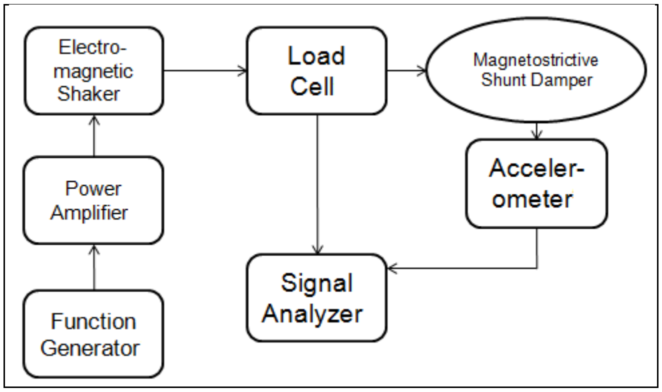

Figure 5. Test setup.

Four different shunt configurations were tested: a resistor with no capacitor, a capacitor with no resistor, a resistor and capacitor in series, and a resistor and capacitor in parallel. A CS-301 precision capacitance substitute was used as the capacitor and a RS-201W wide range precision resistance substitute was used as the resistor. The capacitance box had a range from 1 to 99.9999 μF and the resistance box had a range from 0.1 to 10^8 Ω. An Agilent DSO-X 3014A digital signal oscilloscope was used to determine the phase between the voltage output of the shunt and reading from the accelerometer.

3. Results and Discussion

The resistor and the capacitor both showed the ability to increase the damping of the structure. As seen in figure 6, the resonant peak is greatly decreased by applying only the resistive shunt. There is even a greater decrease when only the capacitive shunt is applied.

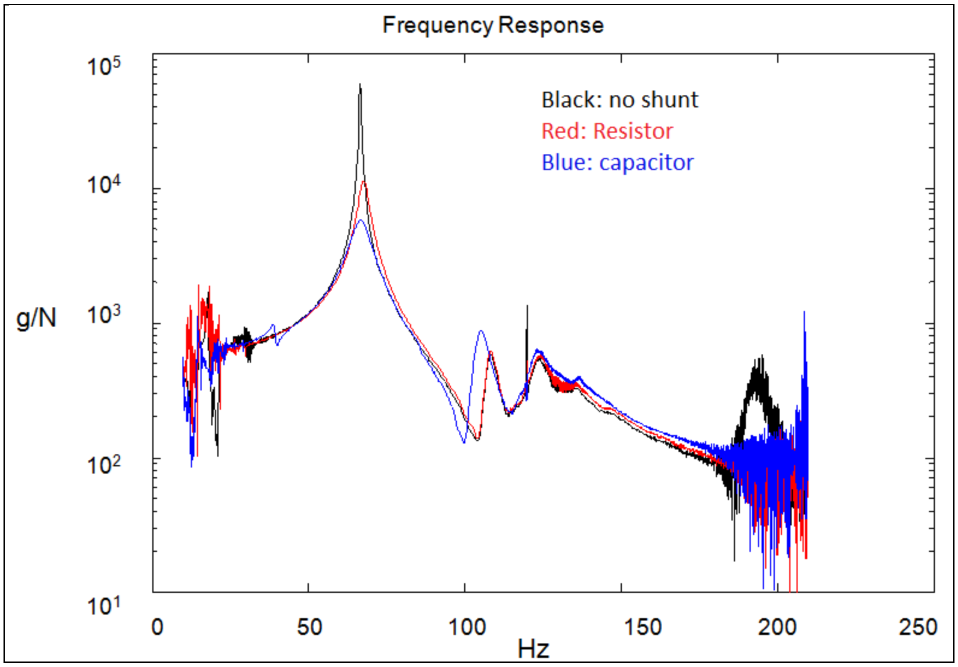

Figure 6. Frequency response without shunt (black), with tuned resistor (red), and with tuned capacitor (blue).

Tuning the resistor was an effective way to increase the damping (figure 7) as it increased the damping ratio by over 400%. The peak performance was observed between 1 and 100 Ω. There is a clear decrease in performance as the resistance approaches 10^4 Ω. The high resistance does not allow for current to pass through the shunt, so the shunt is unable to dissipate the energy.

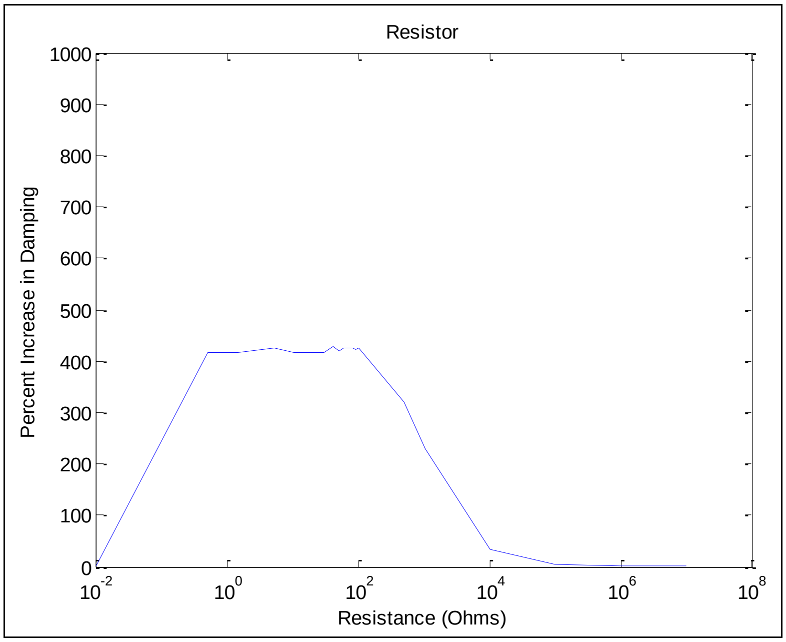

Figure 7. Percent Increase in damping vs. resistance plot.

Tuning the capacitor was an even more effective way to increase the damping (figure 8) as it increased it by over 900%. The theoretical optimal capacitance value was where the acceleration and voltage are 180° out of phase. This occurred at around 8.5 μF. However the highest damping occurred at a capacitance of 6 μF. At 6 μF, the phase was around 165°. This method was over twice as effective as only using a resistor.

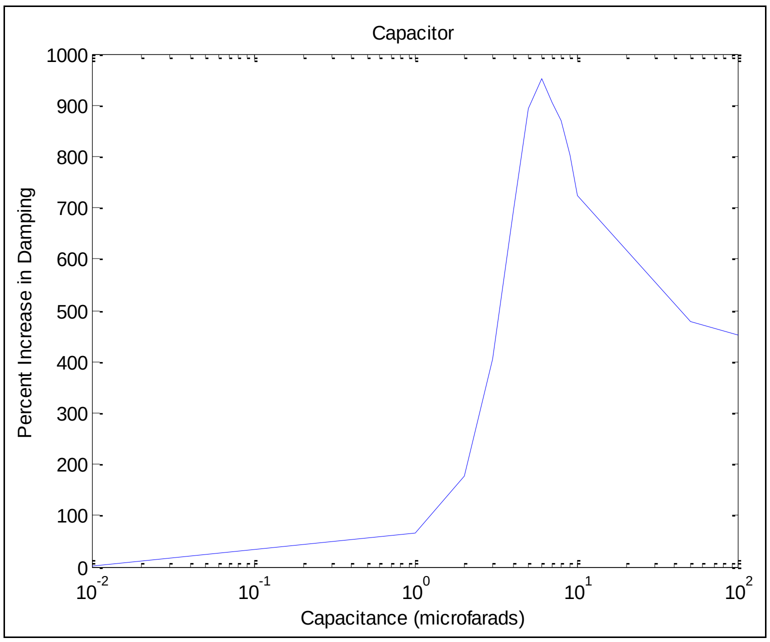

Figure 8. Percent Increase in damping vs. capacitance plot.

Using both the resistor and the capacitor in parallel was less effective within the range of the test. At the effective resistance values determined earlier, between 1 and 100 Ω, the current would run through the capacitor so that the resistor could not dissipate the energy, effectively. However, the resistor also affected some of the phase shift (maybe the capacitance effect within the resistor) so that it was not effectively using the eddy currents to dampen the structure. When the resistance was increased to the ineffective values above 10^4 Ω, the configuration acted similarly to the lone capacitor. The limited current through the resistor was not affecting the capacitor's ability to change the phase. However, because it was still dissipating some energy, the eddy currents were not as effective. It showed that the eddy currents were a more effective way to dampen the structure.

Using both the resistor and the capacitor in series was similar to using the capacitor. However, the resistor still dissipated energy that could be better used in the eddy. This method was more effective than just using a resistor and less effective than just using a capacitor.

4. Summary and Conclusions

Different shunt configurations were tested to determine which one would optimize the performance of the magnetostrictive shunt damper. The different shunt configurations were a resistor with no capacitor, a capacitor with no resistor, a resistor and capacitor in series, and a resistor and capacitor in parallel. The frequency response function was used to determine the damping ratio at multiple resistance and capacitance values. The most effective shunt was the tuned capacitor with an over 900% increase in damping. This was over twice as effective as the tuned resistor, which achieved an over 400% increase in damping. Using both the resistor and capacitor in the same shunt decreased the effectiveness of the capacitor, which was the most effective means of increasing the damping ratio of the structure.

Determination of how the capacitor affects the magnetostrictive shunt damper is far from conclusive. How eddy currents affect the system needs to be studied and further explanations of the effects of a tuned capacitor should be investigated. The tuned capacitor was the most effective method to increase performance of the shunt within the ranges of this study.

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