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Vibration Isolation with High Strain Shape Memory Alloy Actuators: Case of the impulse disturbance

Danny Grant Vincent Hayward

Department of Electrical Engineering and
Research Centre for Intelligent Machines
McGill University
Montréal, Québec, H3A 2A7, Canada
`grant@cim.mcgill.ca, hayward@cim.mcgill.ca`

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Abstract

Shape Memory Alloys (SMA's) are generally considered to be a slow and imprecise means of actuation. With the SMA actuator designed at McGill University we wish to show the contrary. In this paper, several SMA actuators are used to actively damp an external impulse disturbance on a mass to be isolated from vibrations. The vibration isolation testbed consists of a 'strong' actuator to low-pass the system and a 'fast' antagonistic pair to attenuate the remaining disturbance. Both damping systems use the same basic actuator architecture. A variable structure controller switching on the acceleration error and the jerk is effectively used to dampen out an impulse disturbance within 360 msec.

1 Introduction

Vibration isolation and suppression have many practical applications in various engineering fields, from the stablization of large space structures to the seismic isolation platforms used for sensitive experimentation and manufacturing. The high damping capacity of Shape Memory Alloys (SMA's) is well known [6], and makes them an ideal candidate for vibration isolation both in a passive and active manner. Furthermore, metal isolators have a significant advantage over their more conventional rubber counterparts in the presence of gases, oils, corrosive agents and high temperatures [2], which are typical of manufacturing conditions.

For these reasons, SMA springs [2] [8], straight fibers [1] [10] , and embedded fibers [12] have all been used to control vibrations in cantilever beams and other structures. While meeting with some success, using the SMA in such a manner results in low bandwidth control and therefore relatively slow suppression of the disturbance vibrations. With the SMA actuators designed at McGill University [3] it is shown that SMA's can be used both in a passive and active fashion to suppress vibrations rapidly (360 msec). In this paper a method to isolate loads from seismic vibrations using SMA actuators is presented.

2 Vibration Isolation with SMA's

Passive isolation systems can attenuate resonant peaks with the basic tradeoff of increasing the transmission of frequencies beyond the natural frequency of the system. This is due to the high forces required to dampen the resonance which are then transmitted at higher frequencies[7]. Active isolation systems, on the other hand, do not suffer from this drawback and can be tuned to dampen the resonance and roll off the high frequency transmission. However, they require high actuator strength. As a consequence, multi-stage vibration cancellation mounts, using both active and passive damping, have been proposed [9]. The passive stage generally low-passes and attenuates the broad band disturbance, while an active stage is used to augment low frequency damping and provide attenuation in critical frequency ranges.

With the rich design space of the SMA actuator[3], it is possible to design actuators for both the passive and active stages, using the same basic architecture. A diagram of this multi-stage approach is shown in Figure 1.

The basic idea is to combine a 'strong' actuator to low-pass the system and a 'fast' antagonistic pair to

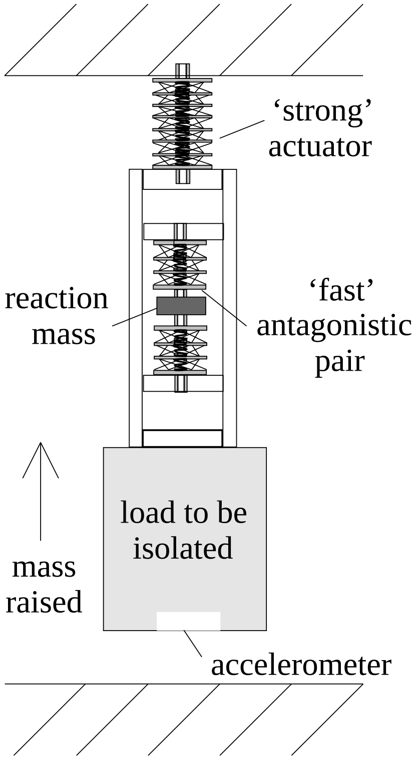


Figure 1: Multi-stage approach

attenuate the remaining disturbance vibration. The 'strong' actuator was designed to lift the load to be isolated from the ground. Raising the mass in this manner causes any exogenous vibrations to be low-passed. The 'strong' actuator also compensates for the gravity of the mass; in other words, it offsets the DC bias of the system.

The raised arrangement, however, is now similar to a mass on a spring, and has a resonance. An antagonistic pair of 'fast' actuators, manipulating a smaller reaction mass, was designed to actively damp out this resonance from the under-damped 'mass-spring' system.

2.1 'Strong' Actuator

Figure 2 shows the testbed that was constructed to isolate a test load, in this case a 1 kg mass, using the above combination of SMA actuators and a commercial accelerometer, the ADXL05 from Analog Devices.

Recall that the SMA actuator in[3] consists of twelve NiTi fibers woven in a counter rotating helical pattern around supporting disks. The disks are separated by preloading springs that keep the fibers under tension when relaxed. When the fibers are heated, they contract pulling the disks together.

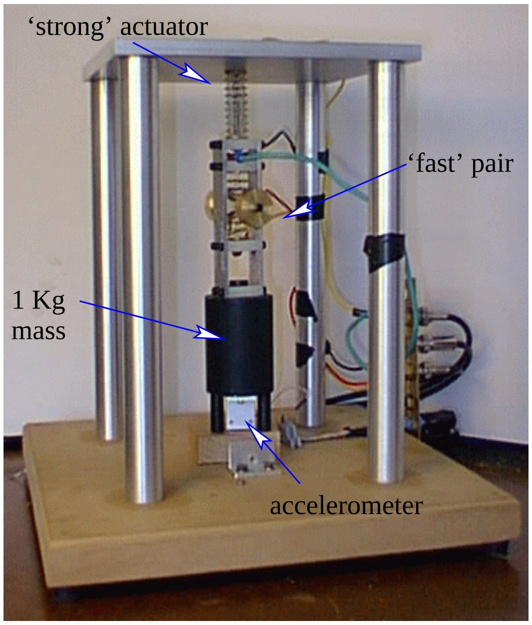


Figure 2: Experimental Setup

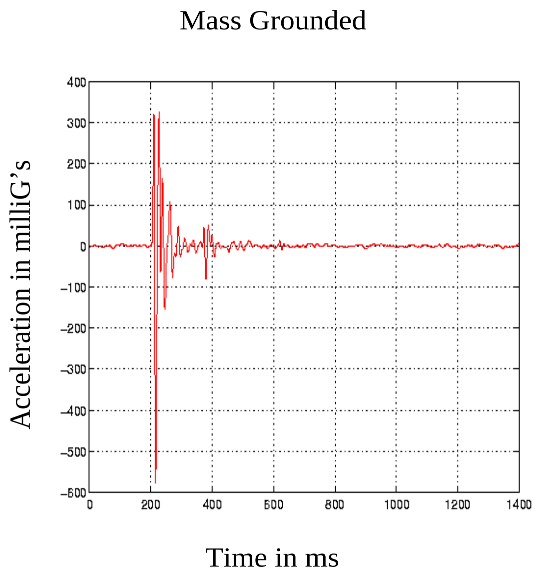
The 'strong' actuator in the passive damping system was designed using 250 micron fibers. It was made with 10 disks 17 mm in diameter, producing 9 identical cells with an overall length of 42 mm.

The 'strong' actuator was over designed in strength so that when the mass was raised, the shape memory material would be only partially in the Austenite phase. This allowed for a lower spring constant and a lower cutoff frequency, since the shape memory material is much stiffer in the Austenite phase than the Martensite phase.

The 'strong' actuator in this case was controlled open loop, and therefore was being used passively. It would not be difficult to close the loop with a position sensor, allowing the spring coefficient to be tuned to suit different applications. This would effectively make the 'strong' actuator semi-active.

2.2 Impulse Disturbance

Figure 3 shows the response of the system to an impulse disturbance at t = 200 msec. An impulse was chosen as a disturbance throughout this paper as it represents a typical and severe disturbance to a seismic isolation platform. When the mass is grounded, the disturbance creates a large amplitude spike (peak to peak .9 G) with a high frequency content. When the mass is raised, it can be seen that the system effectively low-passes the impulse disturbance , however it is now only slightly damped. The resonant frequency of this 'mass-spring' system is 12.5 Hz and its settling time is 8 seconds.


Mass Grounded

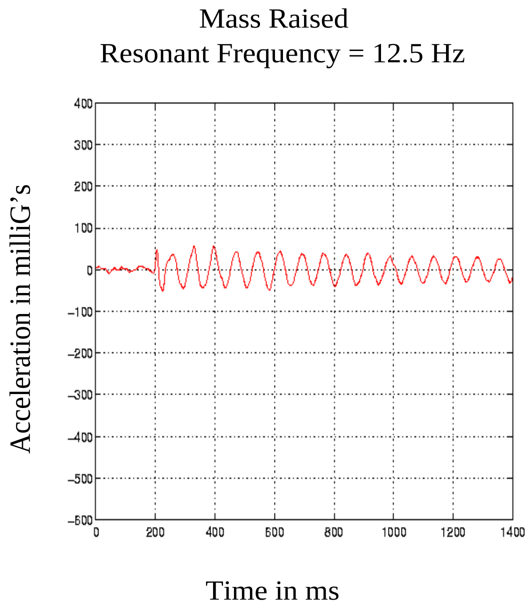

Mass Raised
Resonant Frequency = 12.5 Hz

Figure 3: Low passing the System

2.3 'Fast' Antagonistic Pair

A reaction mass of 100 g was used by the antagonistic pair to counter-act the remaining resonance of the 'mass-spring' system. The 'fast' actuators were designed using 100 micron fibers . This allowed rapid cooling in ambient air, while the many fibers in parallel provided ample actuator authority. The actuators were constructed with the same weave pattern as the 'strong' actuator, but were made with only 4 support disks. This produced 3 identical cells with an overall actuator length of 17 mm. Using the actuators in an antagonistic fashion results in an improved system response. The response time of the actuator system now depends strongly on heat activation, which can be tuned according to the input current amplitude.

3 Controller

Acceleration is a natural measurement to use when dealing with a mass's vibration. It is generally noisy however, so care must be taken in designing the feedback control. A variable structure controller can partially resolve this difficulty, since only inequality conditions need to be satisfied in the design [11]. Switching according to the sign of the acceleration error provides for a more robust system, as only the sign is needed rather than the full version of the noisy signal. This robustness also makes the controller easy to design and tune. In order to determine an appropriate feedback current waveform for this switching, the open loop responses of the systems were examined.

3.1 Open Loop Position

Upon examining the open loop position response of a pair of antagonistic actuators, it can be seen in Figure 4 that the pair undergoes a change in acceleration only at the beginning and at the end of the heating curve. In other words, the actuator pair quickly reach a constant velocity and further heating by the current pulse moves them along in a linear fashion. This is not surprising since a simple model for the actuator's position is given by an ideal integrator [4].

After approximately 20 msec, further heating does not add to the actuator acceleration. The rate of change from the Martensite phase to the Austenite phase quickly reaches a constant. Therefore, in order to avoid unnecessary heating of the antagonistic pair, the driving current pulses should not exceed 20 msec.

3.2 Open Loop Acceleration

The open loop response of the antagonistic pair can be seen in Figure 5. The acceleration measured is the

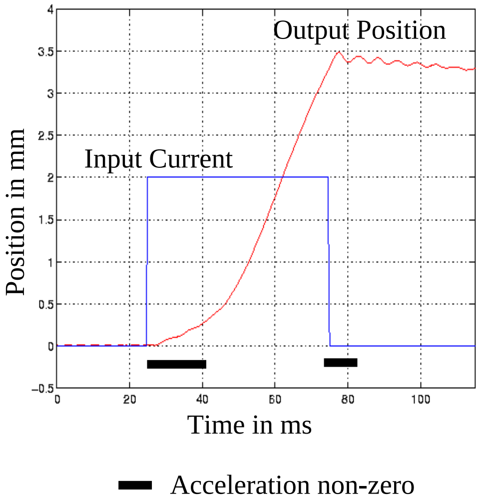


Figure 4: Open Loop Position Response

acceleration of the 'mass-spring' system, that is when the 1 kg mass is raised.

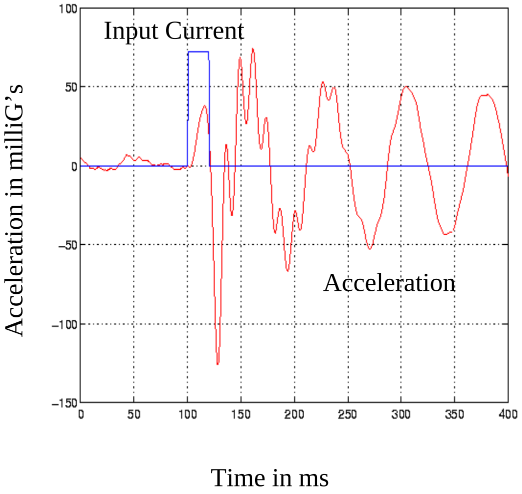


Figure 5: Open Loop Acceleration Response

The current input is a 20 msec pulse of 10 amps. The fibers in the SMA actuator are electrically connected in parallel so the current in each individual fiber is divided by twelve. Each current pulse creates a change in acceleration during and after the end of the pulse. This corresponds to the reaction mass accelerating when current is applied and then decelerating when the heating is stopped. The second order dynamics of the antagonistic pair's free motion can be seen superimposed on the resonant frequency of the 'spring-mass' system. The antagonistic pair has a resonant peak at 77 Hz which dampens out in approximately 160 msec. Note that the peak of the deceleration pulse is significantly larger than the peak of acceleration pulse. This is independent of the gravity acting on the reaction mass.

3.3 Switching Controller

In an effort to keep the control scheme simple, a variable structure switching controller was designed using the acceleration and the jerk as shown in Figure 6. The derivative of the acceleration was obtained in software by an adaptive windowing technique [5] to prevent spurious switches on the noise.

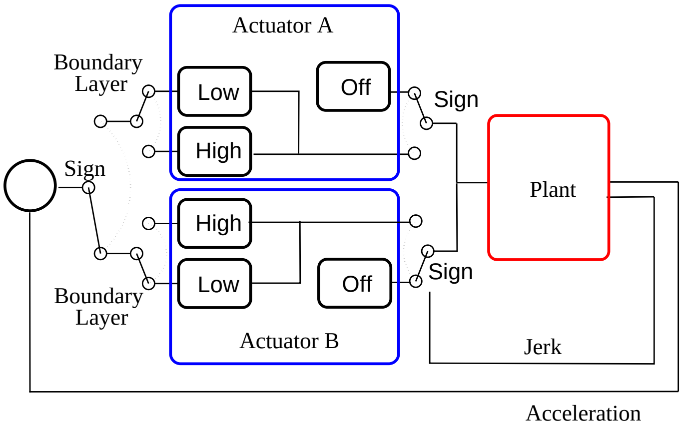


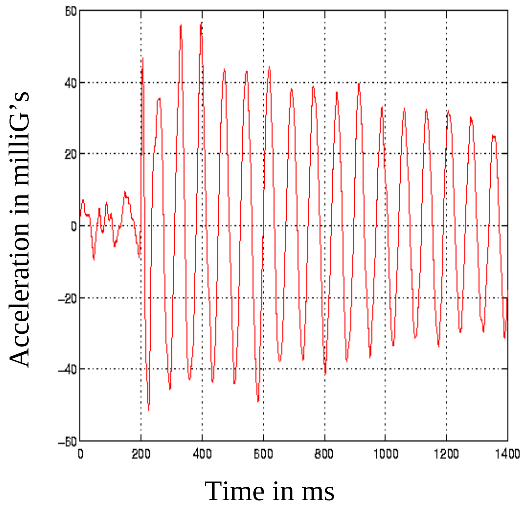
Figure 6: Switching Controller

Essentially the controller switches according to the sign of the acceleration error, sending 20 msec pulses to the respective antagonistic actuators. A boundary layer is placed around the set point to realize the dual goals of a rapid and a stable response. A different constant magnitude pulse is used inside and outside the boundary layer. To prevent unnecessary heating, the jerk signal is used to shut the current off if the acceleration saturates.

4 Experimental Results

Figure 7 shows the result of applying this controller to the antagonistic pair, that is adding the active damping stage. Again the disturbance is chosen to be an impulse applied at t = 200 msec. After a few oscillations, the controller is able to dampen out the resonance of the 'mass-spring' system.

Mass Raised



Active Damping

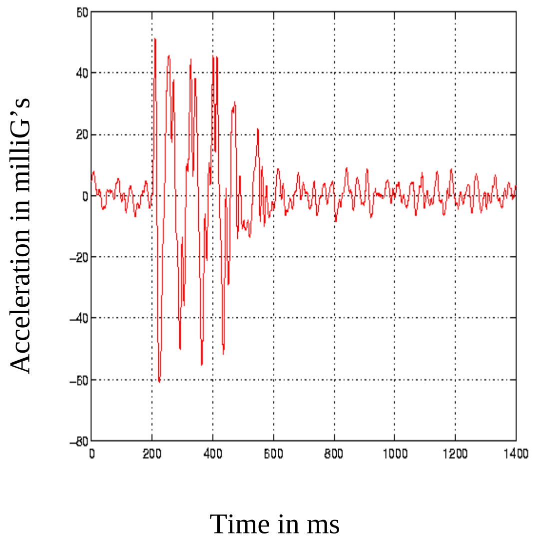


Figure 7: Effect of Active Damping

The dynamics of the active pair can again be seen superimposed on the measured acceleration error. The reaction mass removes energy from the system on each oscillation, finally settling down to the noise level after 360 msec. What the controller in effect does is drive the reaction mass so that the net acceleration is out of phase with the disturbance, effectively cancelling it. The controller accomplishes this by actually moving the reaction mass in the same direction as the disturbance and relying on the larger peak of deceleration to remove the energy from the system.

The combination of the active and passive damping systems results in the attenuation of the impulse disturbance by 87 % within 360 msec.

5 Conclusions

While the results of this paper show that the SMA actuator can be used effectively in active and passive vibration isolation, they also open questions for future research. Current work is focused on widening the class of disturbance inputs, in particular for the case of a persisting disturbance. Different feedback current waveforms are being explored, for example triangle pulses, to decouple the acceleration and deceleration phases of the antagonistic pair. Alternative designs for the antagonistic pair are also being considered, in particular, the chaining of several pairs to provide continual compensation when a single pair saturates in acceleration.

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