

ON PIEZOELECTRIC ENERGY CONVERSION FOR ELECTRONIC PASSIVE DAMPING ENHANCEMENT

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ABSTRACT

To meet their performance requirements, large orbiting space structures are expected to need both passive and active vibration suppression systems. Ideally these systems would replace structural members with members possessing both structural and dissipative properties.

The design and development of concepts of enhanced-damping struts that employ the mechanical/electrical conversion properties of piezoelectric materials is presented. Rather than mechanically dissipating energy, the strain-induced mechanical vibration is converted to electrical energy which is shunted through a tuned electrical network. The networks use a shunted inductance which acts in concert with the inherent reactance of the piezoelectric material to maximize the current dissipated.

Because of the relatively low structural frequencies and large piezoelectric capacitance, inductances on the order of tens to hundreds of Henries are required. A means of using operational amplifiers to simulate the inductance is presented. This substitution eliminates the substantial dead weight of the inductance, and allows for fine-tuning and programming of the inductance to match variations in frequency. A means of adding damping for several frequencies is given. Finally, experimental results are presented.

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INTRODUCTION

Many types of spacecraft are expected to need shape control and structural vibration suppression systems to meet their performance requirements. Spacecraft operating conditions and on-board systems can induce unacceptable structural vibrations requiring many minutes to naturally dissipate. Systems require precise spatial positioning of their components, and such motion can result in the need to introduce some means of vibration dissipation to the structure. This dissipation can take the form of some passive damping mechanism, shape controls, an active vibration control system, or a combination of passive and active systems.

This investigation is concerned with the theoretical modelling and experimental implementation of piezoelectric struts in a generic truss structure. Our recent efforts in this area include struts currently under development using a composite material with embedded Lead Zirconate Titanate piezoelectric ceramic materials (PZTs). Using the piezoelectric effect, the embedded PZTs can act both as actuators and sensors for a shape or vibration control system. The actuators convert the electric field generated by an applied voltage into a mechanical strain, which may elongate or shorten the PZT. Conversely, the sensors convert mechanical strain due to motion into a voltage which may be used to monitor the structure's shape or vibration.

The piezoelectric struts were used to enhance the structure's dissipation. The PZT terminals were shunted with resistor or resistor/inductor networks [1,2], which dissipated the electrical voltage piezoelectrically generated by the structure's motion. Results of choosing the electric elements in the network to tune for a structure's natural frequency will be presented, and the means used to damp two modes simultaneously will be shown. A circuit consisting only of resistors, capacitors, and operational amplifiers simulating an inductance will be shown.

1. THE MDSSC CSI TRUSS

The MDSSC CSI (Control Structure Interaction) Truss has been assembled to serve as a testbed for a wide variety of CSI investigations, including various passive and active control technologies and their practical implementation. It consists of Meroform aluminum and Plexiglass struts and steel nodes, and may consist of up to nineteen bays of rectangular trusswork with diagonal members. The Plexiglass struts may easily be moved to alter the structural frequencies, and any member may be replaced by piezoelectric active struts manufactured by MDSSC. The CSI truss is shown in Figure 1.

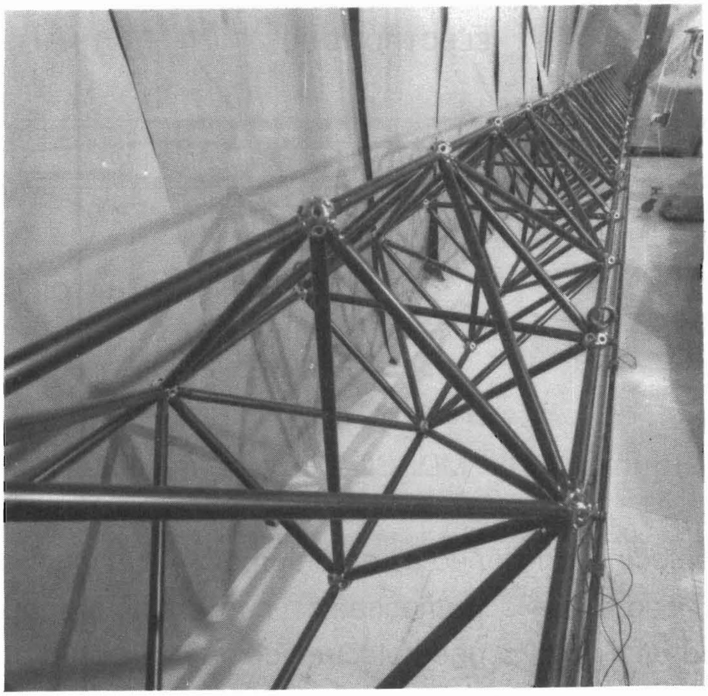

Figure 1. The MDSSC CSI Truss testbed.

The CSI truss is suspended by eight soft springs simulating a "free-free" support system. The spring supports provide pendulum modal frequencies less than 0.5 Hz for all six quasi-rigid body modes. As this is significantly lower than any of the structural mode frequencies, the suspension can be considered "zero stiffness" as far as coupling issues are concerned.

For passive and active control investigations, MDSSC fabricated a number of piezoelectric struts, each consisting of a number of lead zirconate titanate (PZT) hollow cylinder segments wrapped with a fiberglass/epoxy outer coating. The PZT segments were polarized so that an electric field applied between the outer radius and the inner radius created axial deformation. Mechanically, the segments were connected in series, and electrically all but one of the cylindrical rings were connected in parallel.

The remaining segment was electrically isolated so that it could be used independently as a strain rate sensor. Figure 2 shows the design of the MDSSC-fabricated piezoelectric struts. The design was modified from one used by researchers at MIT.

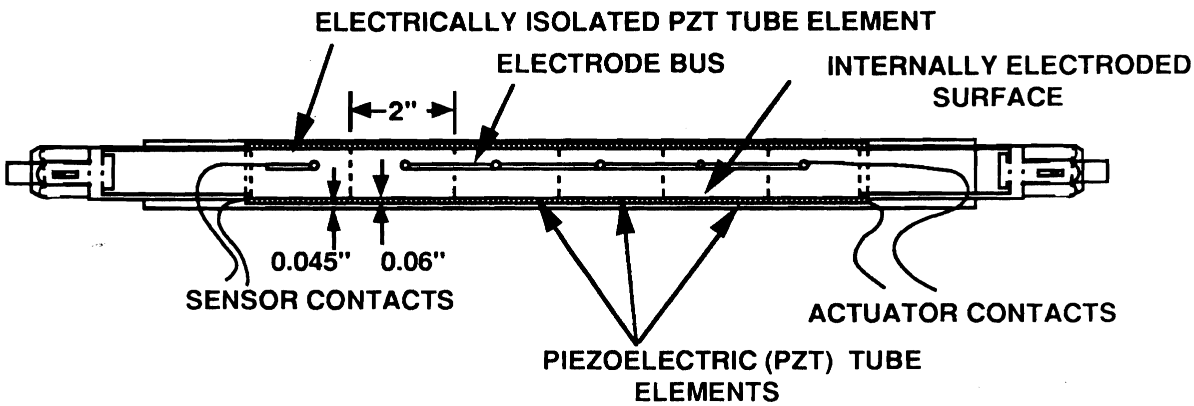

Figure 2. The MDSSC Piezoelectric Strut.

In this work, the piezoelectric functioned as a portion of a vibration dissipation system, where the PZT struts used their electromechanical conversion properties to couple vibrationally-generated energy to a tuned electronic shunt circuit to dissipate energy. A second application was to use the voltage observed at the terminals of the isolated segment of the piezoelectric members as a direct readout of vibrational amplitude. With their very high voltage output, PZTs approach the qualities of ideal sensors.

2. ENHANCEMENT OF DAMPING USING A TUNED ELECTRONIC SHUNT

When a structure is vibrating, components of the assembly are mechanically strained. Piezoelectric materials convert this mechanical strain to electric potential, which allows the addition of an electrical network to extract energy. Hagood et al [1,2] have shown the results of adding a passive shunt to a truss with piezoelectric members. Their truss was of similar construction to the MDSSC CSI truss, except that it was shorter and had twice as many piezoelectric struts. Their experimentation employed both resistive shunting and combined resistive/inductive shunting.

Piezoelectric materials under external excitation behave similar to a capacitance electrically in parallel with a voltage source (see Figure 3). A pure resistance is the only means to dissipate energy, because both capacitive and inductive elements can store energy, but not dissipate it. References [1] and [2] showed that there are optimal values for either resistive or inductive/resistive shunts, and the optima were determined by energy dissipation relationships having to do with cancelling the inductive and capacitive reactance at the structure's resonant frequencies.

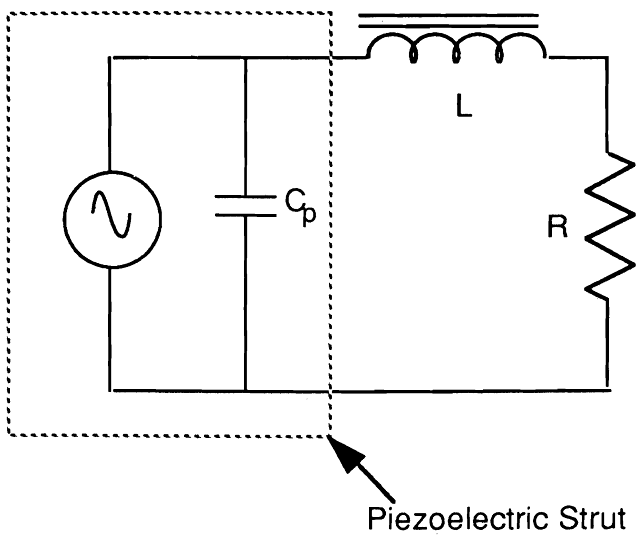

Figure 3. Equivalent Electric Circuit for a Piezoelectric Material and Shunt

Because of the low frequencies involved (from under ten to hundreds of Hertz), large values of inductance are usually required, because the natural frequencies of the attached shunt are related by the following, where L is the added inductance, and C_p is the capacitance of the piezoelectric:

$$f_n \sim (LC_p)^{-1/2} \quad (1)$$

With f_n around 10 Hz and C_p about 1 μF, the value of L computed from Eq. (1) is in the hundreds of Henries. Inductors in this size range are very heavy and possess significant internal resistance, usually higher than that for optimum dissipation. Reducing the resistance or increasing the "Q" of the inductors may be accomplished at the expense of additional mass, by increasing the gauge of the wire and the mass of the inductive material. This is contrary to mass/payload constraints for large space structures.

For this work, MDSSC designed "active" inductors using operational amplifiers and passive circuitry to replace the large mass associated with the necessary values of passive inductance necessary. This was done with a pair of integrated circuit operational amplifiers connected as a gyrator[3], which can produce values ranging from hundreds to thousands of Henries with just a few simple electronic components. Operational amplifiers and a few passive components are all that is required. The electronic circuit used to simulate a large inductance is shown in Figure 4. The value of the simulated inductance may be easily changed by adjusting the variable resistor.

One difficulty was related to the EMF generated by current through the large inductance. Voltage on the inductor may be computed by the relation

$$V = L \times di/dt, \tag{2}$$

where V is the inductor voltage, L is the inductance in Henries, and di/dt is the rate of change of the current through the inductor. It may be seen from Eq. (2) that for moderate currents and inductance in the hundreds of Henries, it does not take long to exceed the normal ±15V range of a common operational amplifier. This indicates that damping performance is likely to be improved at higher current levels corresponding to higher vibration levels with the application of operational amplifiers with higher voltage characteristics.

The use of operational amplifier circuitry to replace passive inductances may mean that it is possible to have passive damping circuits monitor the frequencies to which they are subjected and alter their own characteristics in order to optimize their behavior. This idea is similar to the AFC (Automatic Frequency Control) circuitry used on FM radios to track frequency shifts in commercial broadcasting stations.

The results of applying a single-mode tuned shunt containing an active inductor to the first bending mode are shown in Figure 5. Notice that both the amplitude and frequency drop upon application of the tuned shunt, just a a mechanical system behaves with the application of a viscous damper. The amplitude drops 11 dB, corresponding to a damping ratio increase from 0.068% to 0.25% of critical.

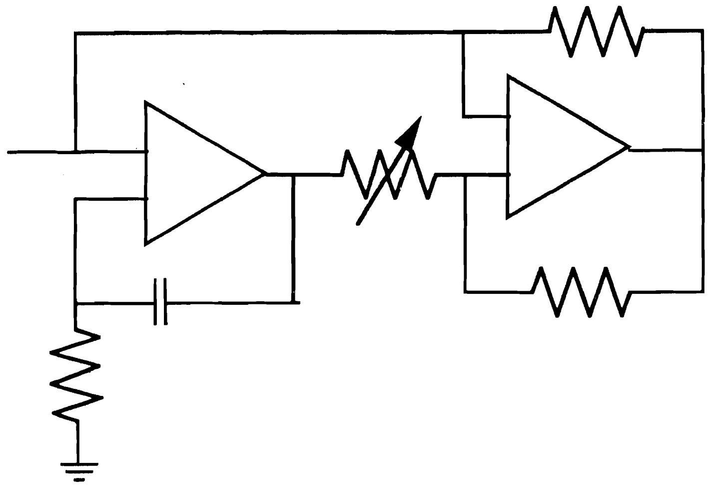

Figure 4. Operational Amplifier Simulated Inductor.

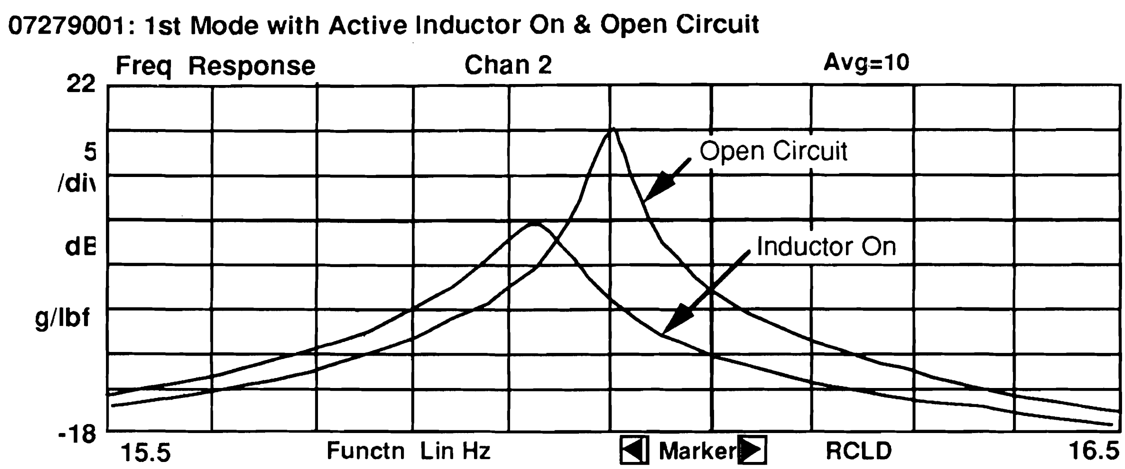

Figure 5. Damping Increase Obtained Through The Use of Simulated Inductor.

To be practical, a vibration dissipation system must work on a range of frequencies, not just a single mode of vibration. This means that added circuitry must be tuned for other modes. Because of mutual loading effects, adding a second shunt circuit "detunes" the first shunt as well as its own settings, so that these effects mst be considered in the design phase. The configuration may be analyzed somewhat easily by iteration, but an expanded theory for synthesis of multiple mode shunts is presently under development.

An example two-mode shunt is shown in Figure 6. It adds a second parallel *LC* network to the original shunt circuitry. Such a configuration simultaneously damped the first and third mode of the MDSSC CSI truss, as shown in Table I. The second mode was not targeted because the piezoelectric struts have little participation and thus effectiveness on this mode.

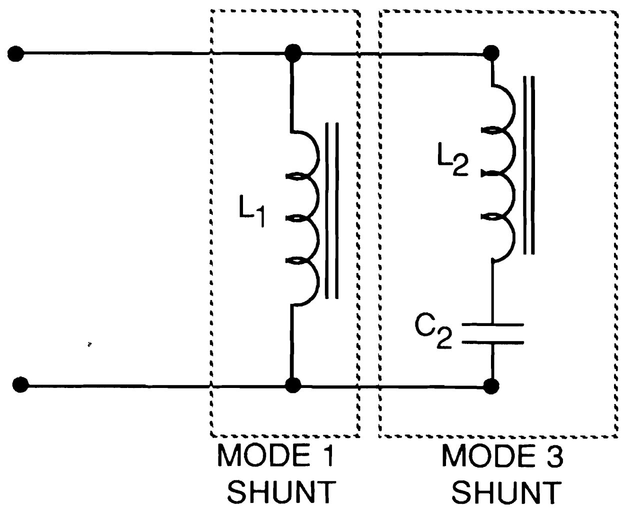

Figure 6. Electric Circuit Depiction of Two-Mode Shunt

TABLE I. RESULTS OF TWO-MODE SHUNT DAMPING EXPERIMENT

Mode	Damping Ratio (% Critical)		% Increase	dB reduction
	Unshunted	Shunted		
1	0.0397	0.146	368	11.3
3	0.0381	0.200	525	14.4

CONCLUSIONS

This paper presents several concepts that are intended to enhance the available damping created by structural members in a vibrating mechanical system. The damping is enhanced by dissipating the energy created by mechanical-electrical conversion of the piezoelectric materials within an electronic circuit.

We have used the piezoelectric members of the MDSSC CSI Truss in a demonstration of various vibration dissipation techniques. In all of these techniques, one or more tuned shunts is connected to the terminals of a piezoelectric truss element and tuned to create a resonant circuit for enhanced passive damping. We have shown that heavy passive inductances may be replaced by lightweight electronic circuits, and that a tuned shunt circuit may be made to simultaneously dissipate two modes of vibration. Due to mutual loading effects between multiple shunts, there are still analysis difficulties related to their design and synthesis.

RECOMMENDATIONS

We are working to develop an active inductor circuit that can tolerate higher voltages without saturation of its operational amplifiers. This development will be coupled with the development of a more practical theory for the multiple shunt analysis that will reduce or eliminate the trial and error methods used for this study. A wideband shunt circuit will also be investigated, as will self-tuning (AFC) circuitry.

REFERENCES

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