A New Semi-Active Piezoelectric-Based Friction Damper

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ABSTRACT

A new way to perform vibration control on a single-degree-of-freedom system using a piezoelectric friction damper is developed. The damper consists of an actuator, which is based on a piezoelectric stack with a mechanical amplifying mechanism that provides symmetric forces within the isolator. The advantages of such an actuator are its high bandwidth, actuating response and its ability to operate in vacuum environments such as in space. The damper is constrained to move using an air bearing that produces a virtually ideal single-degree-of-freedom spring-mass system. Within this work, the actuating ability of the friction-based actuator is characterized. The relationship between the force generated by the actuator and the applied voltage was found to be linear. The maximum force generated by the friction damper in this study is 85 N for the specific friction pads used.

Keywords: Vibration control, piezoelectric, friction, damper, actuator

1. INTRODUCTION

The need for vibration isolation is becoming increasingly important for precision structures and sensitive high technology equipment. More reliable devices with a higher bandwidth, smaller size, and lower power requirement are needed. Semi-active control of vibration isolation is an area of much interest due to its potential to provide these characteristics. Piezoelectric actuators have only recently been proposed to be used in vibration isolation[1-7]. However, the development of such a device is still in its infancy.

Friction damping has long been used as an effective and simple method to add passive damping to mechanical systems. It requires only the direct contact of two parts moving relative to each other and it can be incorporated into harsh environments and vacuum environments where the use of elastomeric damping treatments and fluid filled dampers is limited[8]. Ferri and Heck first came up with the idea of varying the normal force in a frictional joint to enhance energy dissipation from a vibrating structure[9]. A semi-active friction damper feeds back an actuation force to the mechanical system whose dynamics can be altered in this way. The properties of the system, such as stiffness and damping can be actively changed through the control of this actuation force.

The development of friction dampers to the extent of other semi-active dampers has been impeded due to three primary reasons. First of all, because of the discontinuity of friction at zero velocity, the differential equation of motion of the dynamic system is dependent on the direction of velocity[8]. Secondly, when the static coefficient of friction is noticeably greater than the kinetic coefficient, the “stick-slip” phenomenon occurs. This phenomenon is caused by the fact that the friction force does not remain constant as a function of some other variable, such as temperature, displacement, time, or velocity. For the two reasons stated, friction dampers are non-linear and will require a non-linear controller.

The third and most important reason friction dampers have not been fully developed is due to the actuator. In past research, the normal force was altered through the use of hydraulics[10]. The main disadvantage of hydraulics is the time delay that is required for the actuator to reach the required pressure. Rapid modulation of the actuation force is not possible and it could cause a backlash effect when used. In a variable friction damper system, the speed with which the actuation force can be adjusted is of utmost importance[6]. Modern electromagnetic actuators are well suited to provide rotational motion (electric motors); however, their use as linear actuators is limited. Although they are capable of

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generating sufficient force and displacement, the large size, weight, electrical demands and cost of these actuators make them currently impractical.

Recently, piezoelectric actuators have been proposed as a method of applying the varying normal force[1-2]. Piezoelectricity is the ability of certain crystalline materials to develop an electric charge proportional to a mechanical stress and vice versa. Piezoelectric materials can generate a significant amount of stress/strain in a constrained condition when exposed to an electric field. This property has been used to suppress excessive vibration of mechanical and aerospace systems and is still an active area of research[2]. Due to their high force and bandwidth capability, piezoelectric actuators appear to be a natural candidate for use in friction dampers. However until only recently, the maximum (freely loaded) mechanical strain of these devices did not exceed 0.1%. This means that an actuator 1 inch long could only deflect 0.001 inch (significantly less under load). As a result, the development of a practical frictional damper has been hampered.

A flextensional piezoelectric amplifier (using an ordinary piezoelectric material) has recently been developed (FPA-1700, Dynamic Structures and Materials, LLC) that can generate a 1.6 mm displacement having a load of 10 lbs. This specific actuator was chosen to be implemented in the developed vibration isolator due to its high displacement capability and also due to the inherent characteristics of piezoelectric actuators, which make them favorable when compared with other actuators. They have the potential to be effective over a wide frequency range with high-speed actuation, low power consumption, reliability and compactness.

Within this work, a novel semi-active friction damper is created. The actuating ability of the damper is quantified through an experiment. This damper has potential application to space environments in which other viscous dampers as well as electro-rheological and magneto-rheological dampers are not suitable. It may also have application to civil engineering structures, parallel platform mechanisms, large space structures, and vehicle suspensions.

2. THEORETICAL REVIEW

The system tested in this work can be modeled as shown in Figure 1.

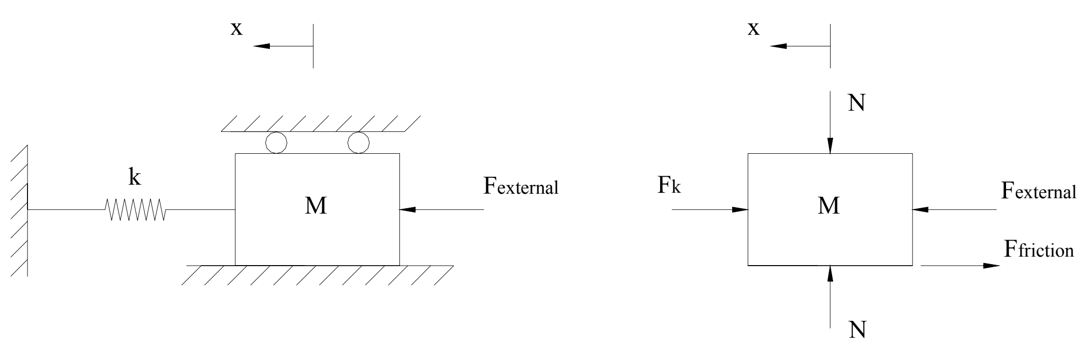

Figure 1: Schematic drawing and free body diagram

The forces acting on the moving mass are the spring force, the friction force and the external force applied by the shaker. The sum of these forces provides the inertial force. Therefore,

$$\sum F = m\ddot{x} = -F_{spring} - F_{friction} + F_{external} \tag{1}$$

The acceleration and the applied external force are measured using an accelerometer and a force transducer, respectively. While for the system identification experiments, the spring is included in the damper, it is removed from the system for the friction force experiments. Therefore, by rearranging Equation (1) and taking out the spring force, it is possible to measure the friction force generated by the actuator. Therefore, the friction is given by,

$$F_{friction} = F_{external} - m\ddot{x} \tag{2}$$

Equation (2) is used to quantify the performance of the new semi-active friction damper. The acceleration and the external force are measured in order to compute the frictional force capabilities of the damper.

3. EXPERIMENTAL SETUP

The actuator that is used within this work is the FPA-1700 Low Voltage Piezoelectric Actuator by Dynamic Structures & Materials, LLC and is shown in Figure 2. The actuator incorporates a shape memory alloy preload wire for bi-directional motion and a titanium flexure-based amplification mechanism. The peak output stroke of the actuator when it is not loaded is approximately 1.6 mm. The displacement of the mechanism is transmitted through two parallel output plates. The friction pads are kevlar bike disc brake pads (CODA® QPDPAD/BLU) and the housing is stainless steel.

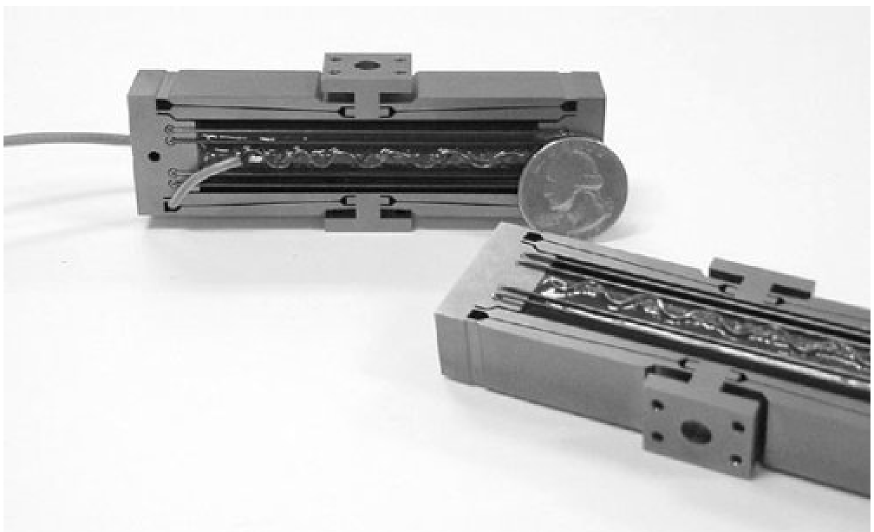

Figure 2: FPA-1700-LV piezoelectric actuator (courtesy of Dynamic Structures & Materials, LLC)

The friction damper in this work consists of several moving and stationary components as shown in Figure 3. A 0.75" diameter shaft is fixed to the base of the damper. Mounted to the shaft is the flextensional mechanical amplifier of the piezoelectric actuator. The moving components consist of the outer housing and the air bearing. The outer housing also comes in contact with the friction pads as it vibrates. The friction pads are fixed to both sides of the actuator so that the normal force that the actuator applies is symmetrical. The normal force provided between the friction pads and the outer housing induces a frictional load, which retards the motion of the outer housing. Within this damper, there is also a spring, which connects the moving housing to the stationary base. With the frictional pads not engaged, the air bearing provides a relatively frictionless contact surface. As a result, the damper is essentially an ideal SDOF system.

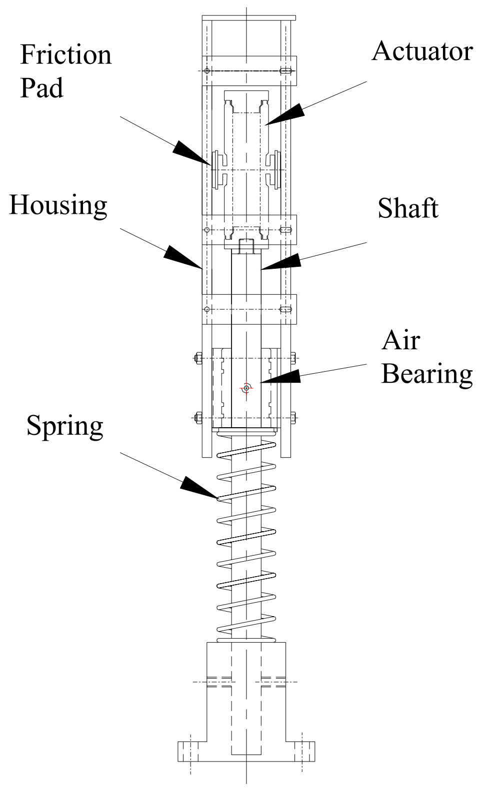

Figure 3: Friction damper (front view)

The vibration isolator has been designed so that the friction damper is fixed horizontally as shown in Figure 4 and Figure 5. The base of the friction damper is screwed onto a vertical steel plate and the moving outer housing is connected to the shaker through the force transducer and the stinger. The shaker is bolted onto two steel plates. It is positioned so that the friction damper's line of symmetry is in line with the central fixing hole of the shaker. The accelerometers are fixed to the outer housing using wax.

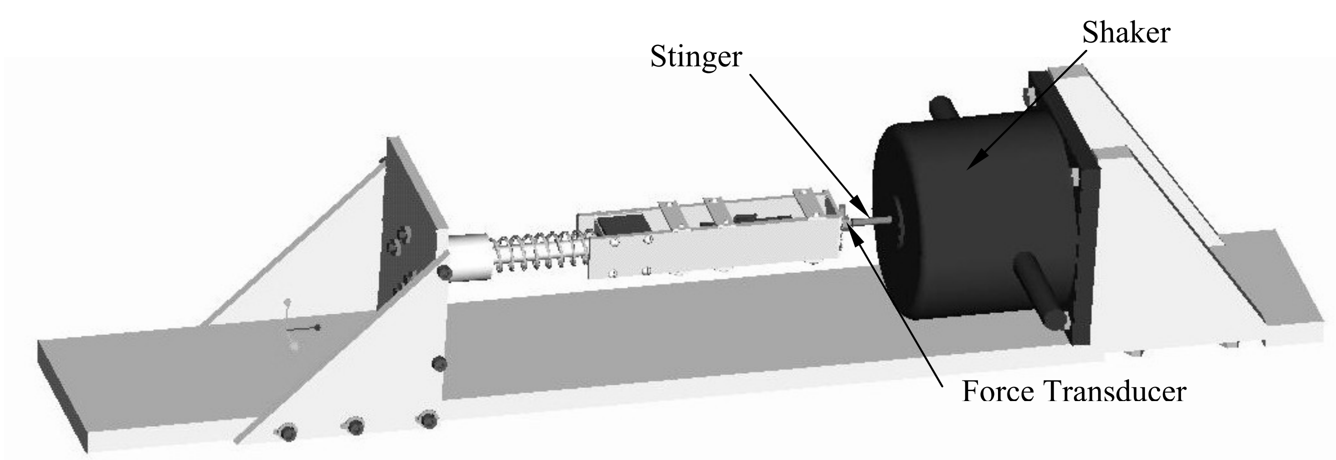

Figure 4: Friction damper with shaker and transducers (3D view)

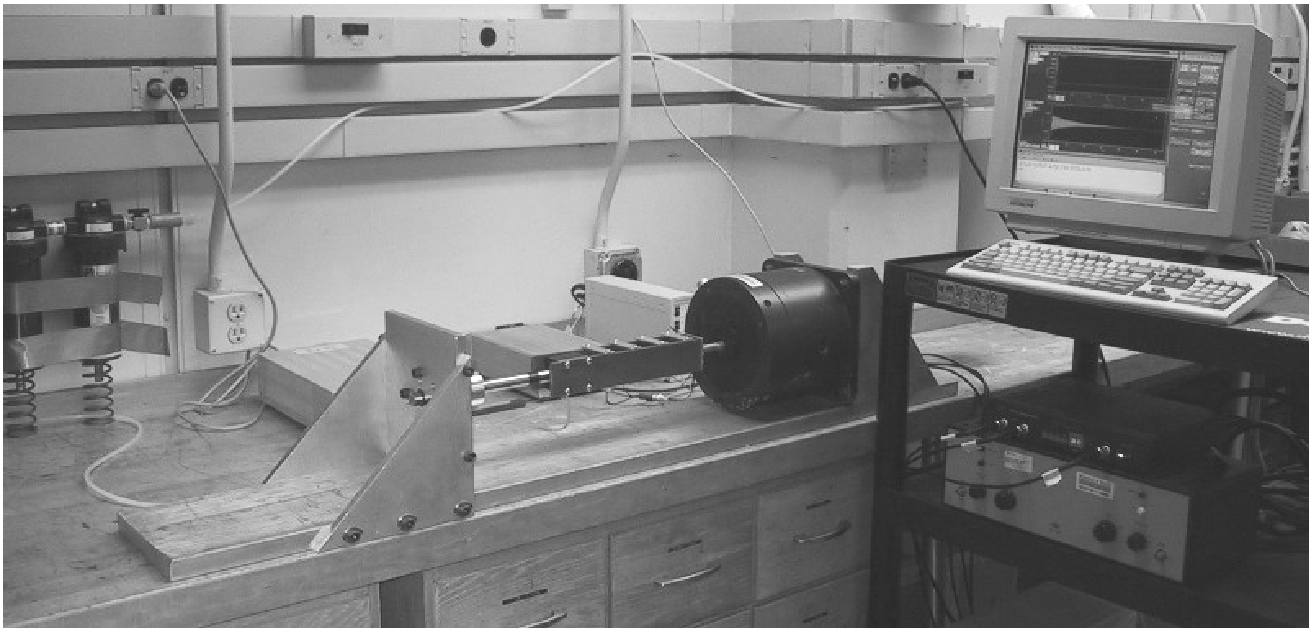

Figure 5: Experimental setup

The signals from all the transducers are fed to the DSPT SigLab (20-42) analyzer through the signal conditioner, model 482A16 from PCB Piezoelectronics. The shaker input signal is generated with the SigLab analyzer. The normal force controller is designed in Simulink®, a MATLAB® plug-in, and implemented in real-time through dSPACE. The actuator input signal is generated in dSPACE and output through the digital-to-analog converter (DAC) as shown in Figure 6.

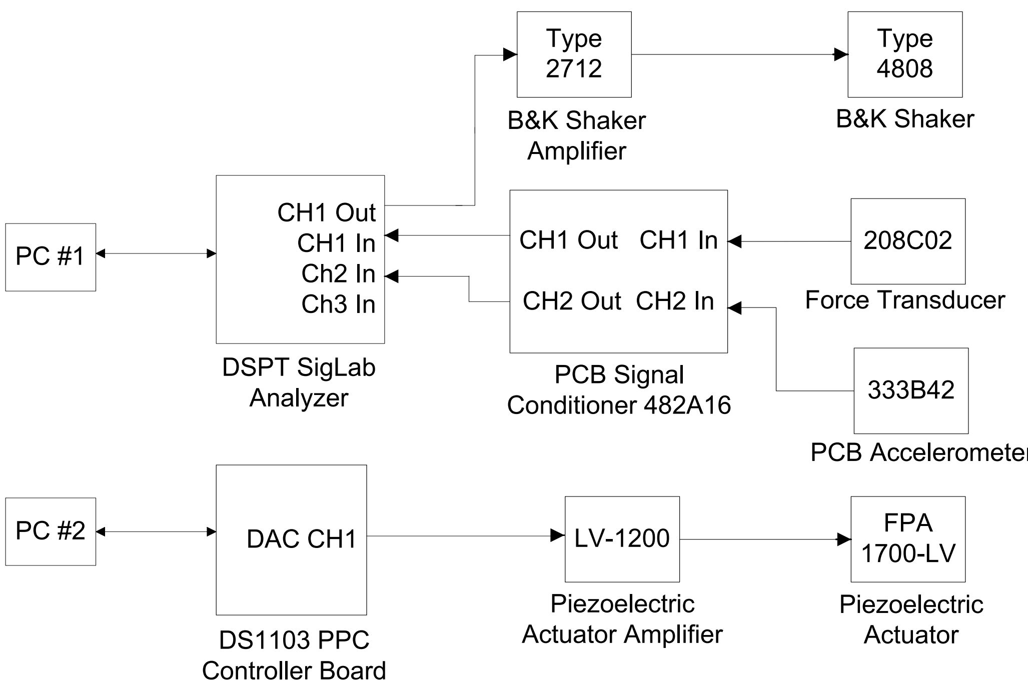

Figure 6: Schematic drawing of the experimental setup

4. RESULTS

Several experiments are carried out in order to characterize the friction force capability of the novel piezoelectric-based isolator. For these experiments, the friction pads are in contact with the outer housing and the spring is removed. Therefore, the difference between the input force and the inertial force yields the friction force induced by the actuator. The results of the experiments for a shaker input voltage of 9 V, excitation frequency of 20 Hz and actuator input voltage of 30 V are displayed in Figure 7.

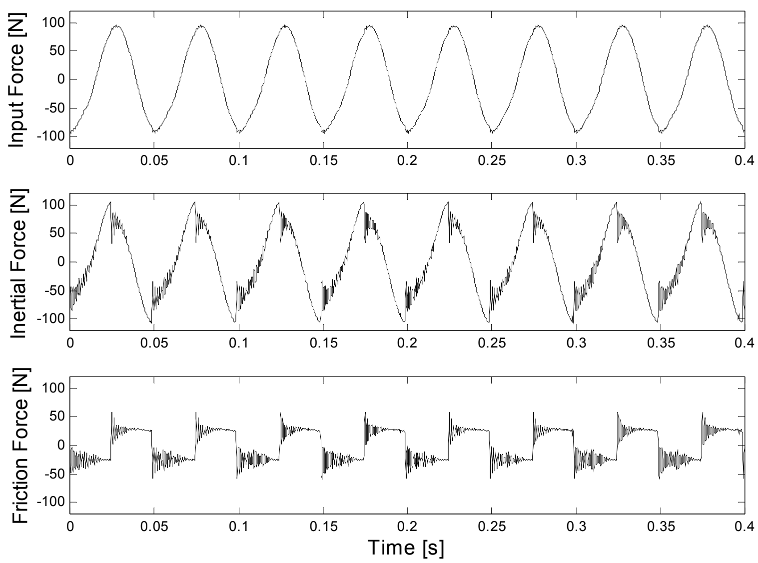

Figure 7: Input force, inertial force and the resulting friction force at 30 V actuator input voltage, 9 V shaker input voltage and 20 Hz excitation frequency

This graph is representative of typical results for the many different test cases measured. Tests were conducted for several different actuator input voltages (30, 60, 90, and 120 V), excitation levels (5, 7, and 9 V), and frequencies (20,25, and 30 Hz). For all these experiments, the mean values of the amplitude of the friction force are calculated using MATLAB®. These values are plotted against the corresponding values of input actuator voltage separately according to the voltage applied to the shaker and the frequency of the excitation.

The mean amplitudes of the friction force induced by the actuator with varying actuator input voltage are shown in Figure 8. The maximum actuator voltage that was tested had a level of 120 V. This was the largest voltage that could be applied without the actuator causing the isolator to stick. In other words, the shaker could not provide sufficient force to cause the isolator to move. If the data in Figure 8 is extrapolated, the maximum value of the friction force that can be induced by the friction damper is found to be approximately 85 N for an actuator input voltage of 150 V.

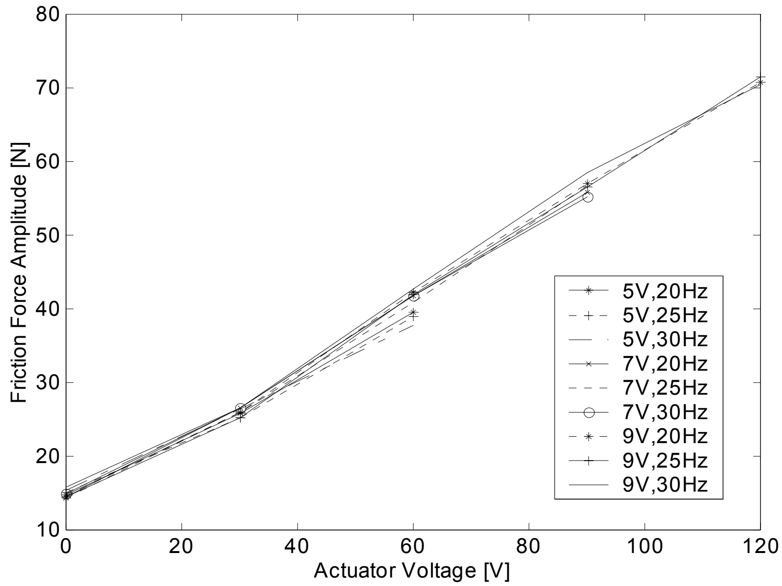

Figure 8: Friction force amplitudes at varying excitation amplitudes and frequencies

In the final experiments that are conducted, the normal force is controlled using dSPACE. The actuator input voltage is increased linearly from 0 V to 150 in about 10 seconds and after a dwell of 1 second, it is decreased again linearly from 150 V to 0 V. As shown in Figure 9, the friction force increases linearly with the actuator input voltage. A summary of the results from the experiments carried out is shown in Table 1.

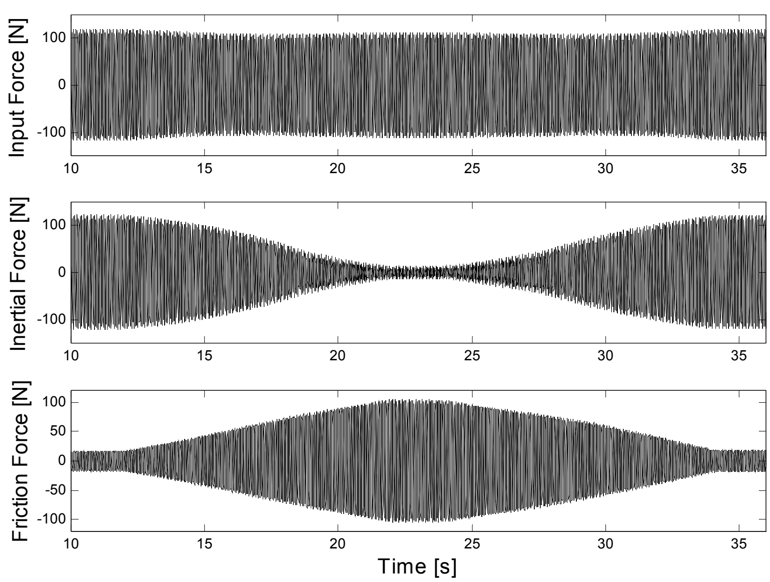

Figure 9: Friction force capability of the actuator when the actuator input voltage is varied linearly

Table 1: Summary of system parameters

Mass of the Moving Elements	1.690 kg
Natural Frequency of System	5.23 Hz
Stiffness of System	1859.5 N/m
Max. Displacement of Actuator	1.6 mm
Max. Stroke of Vibration	12.0 mm
Max. Friction Force Induced by Isolator	85 N

5. CONCLUSIONS

A new type of semi-active friction-based damper has been developed and has the potential to be used in several active vibration control applications. The heart of the damper is a piezoelectric stack with a mechanical amplifying mechanism. Within this work the frictional force capabilities of the actuator have been characterized experimentally. It was determined that the force generated within the isolator is proportional to the input voltage. Additionally, the maximum force capability of the developed friction damper is approximately 85 N for the specific friction pads used.

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