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Active Vibration Control of Civil Structures

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Abstract

This is the final report of a one-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Active vibration control (AVC) of structural and mechanical systems is one of the rapidly advancing areas of engineering research. The multifaceted nature of AVC covers many disciplines, such as sensors and instrumentation, numerical modeling, experimental mechanics, and advanced power systems. This work encompassed a review of the literature on active control of structures focusing both on active control hardware and on control algorithms, a design of an isolation system using magneto-rheological fluid-filled (MRF) dampers and numerical simulations to study the enhanced vibration mitigation effects of this technology.

1. Introduction

Of national importance is the increased protection of the infrastructure and ultimately human lives from the devastation of earthquakes. In addition to life-safety issues, there is the severe economic impact associated with major earthquakes. According to one estimation, a severe earthquake at the New Madrid fault would cause 2.4 trillion dollars in claims as compared to the 30 billion dollars in damage suffered after the Northridge earthquake in January 1994. From the Department of Defense (DiD) standpoint, the Navy alone has \$25 billion worth of facilities in seismically active areas and each year \$200 million worth of new facilities are added to this inventory.

We have examined the application of active vibration control (AVC) to civil structures in an attempt to provide a cost-effective retrofit option for older buildings and to reduce construction cost in new facilities. While performing this study, we have tried to examine

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technology that would be effective for other vibration mitigation problems, such as isolation of submarine decks, thus providing dual-use technology.

Three tasks were accomplished during this project. First, a review of the literature on active control of structures was completed. This review focused both on active control hardware and on control algorithms. Second, a design of an isolation system was developed using magneto-rheological fluid-filled (MRF) dampers. MRF dampers are dampers that can be actively controlled by varying the magnetic field applied to the active fluid. Variations in the magnetic field cause small metallic particles suspended in the fluid to change their alignment thus producing a variation in the effective viscosity exhibited by the fluid. This design can be scaled to a wide variety of uses including civil structures and smaller mechanical components. Finally, numerical simulations were developed of an actively controlled structure to study the enhanced vibration mitigation effects of this technology.

2. Literature Review

An extensive literature review was conducted that focussed on hardware and software aspects of active vibration control. Based on input from the Advanced Research Projects Agency (ARPA), the hardware portion of this review was narrowed to examination of MRF dampers. In general, there is very little literature on MRF dampers or active control of dampers with damping characteristics similar to MRF dampers. No literature was found on the application of this technology to civil engineering systems although literature was found on the application of variable orifice devices to civil engineering systems. There was a large body of literature on active damper control from the automotive industry as well as active and passive vibration control of civil engineering structures. This literature was studied in order to develop active damper hardware designs and additional methodologies for control of these dampers.

3. Isolator Design

The design assumptions used in the development of an active vibration mitigation system were:

- The system should be scalable. That is, the isolator concept should be adaptable to both large civil engineering systems and to smaller mechanical engineering systems.

- The isolator should be able to attenuate multi-degree-of-freedom motion with no knowledge of that motion a priori (referred to in the control literature as no preview).
- The isolator should have modest power requirements.
- The active system should be stable. This requirement implies that the forces applied to the system should not compound the vibration problem.
- The active portion of the isolator should be fail safe. Failure of the active system should not leave the building completely vulnerable to a dynamic excitation.

Considering these design parameters, an isolator was developed with the geometry shown in Fig. 1. This isolator has an elastomer bearing pad that carries the dead weight of the structure. MRF dampers are connected to the top and bottom steel plates of the isolator. These dampers can be oriented at various angles to mitigate different components of motion preferentially. The MRF isolator shown in Fig. 1 has the following attributes:

- It can attenuate inputs in three different directions.
- Multiple MRF dampers can be used to attenuate rotational motion.
- This design is adaptable to a variety of different size structures.
- The actuator is self-centering. After the dynamic input is complete, the structure will be returned to its original position by means of the strain energy stored in the elastomer pad.
- Multiple isolators can be controlled independently to account for local variations in the excitation of the isolated system.
- The isolators fail safe. Without a magnetic field, the dampers still will exhibit passive damping properties.
- There are low power requirements for the generation of the magnetic fields and very fast response times of the fluid to changes in the magnetic field.
- The system is inherently stable. Dampers only apply forces that oppose motion and therefore can not cause instabilities in a system. Because the actively controlled damper only opposes motion, it is often referred to in the literature as semi-active control.

Some of the engineering issues with this system that need to be resolved are:

- Suspension of particles in the MR fluid over time.
- Long-term chemical stability of the fluid.
- Optimal recipe for the fluid.
- Understanding of the magnetic field - viscosity relationship.
- Short-term thermal effects and ambient thermal effects.
- Pressure loads on seals and casing.

4. Numerical Simulations

A one-story building isolated with the semi-active isolators discussed above was modeled numerically. This model is shown in Fig. 2. The numerical models were subject to two types of excitation: impulse excitation indicative of blast loading and earthquake excitation obtained from measured seismic data. The earthquake signals had large sampling errors that needed to be corrected (or more accurately interpolated) in order to compute ground position and velocity. Several routines were written to correct the signals so that they possessed realistic physical characteristics such as zero final velocities.

The response of the isolated structure was simulated with several control laws implemented for the semi-active MRF dampers. The response of the actively controlled structure was compared to the calculated response of the system when no damping was specified and when the maximum damping used in the controlled system was specified in a passive manner. The first control law was designed to minimize the instantaneous transfer of energy to the structure. This simulation proved interesting but not entirely satisfactory. The problem was found that instantaneously optimal solutions do not imply globally optimal solutions. This control scheme produced response of the structure that was inferior to the performance of the maximally damped passive system.

A second control law based on Lyapunov design principles was implemented. The Lyapunov design is also based on an instantaneous minimization. While better than the energy method in many instances, the Lyapunov design suffered from the same pathologies as the energy-based method.

A final control law was implemented to minimize the energy transfer into the building, neglecting energy transfer to the isolator. This control law was found to produce a response in the controlled structure that significantly mitigated its vibration compared to the passive isolation system. This result can be seen clearly in Fig. 3, where the response of the roof is plotted for the three cases that were studied when the structure was subjected to a measured seismic input. The dark line corresponding to the actively controlled system shows that the peak accelerations are significantly reduced when compared to both passively isolated systems.

5. Summary

The results obtained show that a vibration isolator based on an actively controlled MRF damper has the potential to offer enhanced vibration mitigation characteristics over passive dampers. The proposed design can be adapted to large civil structures or smaller

mechanical systems and will mitigate vibrations caused by seismic events as well as those caused by impulsive type loading. A review of the literature shows that the application of MRF damper to civil engineering systems is unique.

Figure 1. Vibration isolator based on magneto-rheological fluid-filled (MRF) dampers.

Structural Parameters: (for 32 isolators)

Mass of the Roof	=1,775,000 lbm
Mass of the Floor	=1,665,000 lbm

Structural Stiffness	=100,000 lbs/in
Isolator Stiffness	=70,400 lbs/in

Structural Damping	=5%
Isolator Damping	=10%

Max MRF Damping Force	=1,760,000 lbs (55,000 lbs each)
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Figure 2. Idealization of an isolated structure.

Figure 3. Roof acceleration response of an isolated structure when subjected to a seismic input.