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Comparison of Control Strategy on Magneto-Rheological Fluid Damper Performance for Impact Reduction

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Abstract. This paper investigates the effects of control strategy selection on the effectiveness of impact reduction control for a magneto-rheological fluid (MRF) damper-based system. The control performance of a passive damper, an MRF damper controlled by skyhook and an MRF damper controlled by a fast practical control are compared. A mechanical system model of a single degree-of-freedom (SDOF) impact isolation system using MRF dampers with different controllers is constructed, and the governing equation for the SDOF impact isolation system is derived. The FPC control algorithm is used to verify the MRF damper performance of the systems. The control performance of the systems under impact loading from various horizontal impact energies is evaluated. The results indicate that the MRF damper with the FPC controller provides much better performance for impact reduction control.

Keywords. *Magneto-rheological fluid damper; impact reduction; control strategy; hybrid control; fast practical control.*

1. Introduction

The magneto-rheological fluid (MRF) damper is a semi-active damper that provides a controllable damping isolation system and has attracted much attention during the past two decades [1-2]. The MR fluid-based actuators and their semi-active control systems are typically employed to absorb or dissipate unwanted energy, such as vibration suppression [3-5] and shock mitigation [6-9]. The MRF damper has been applied to a variety of isolation systems, such as stability and comfort improvement in gun recoil systems [10-12], suspension and engine mounting systems in automobiles [13-16], suspension in railway vehicles [17-19] and seismic isolation systems in civil structures [20]. A semi-active control system based on the MRF damper has also proved useful in mitigating shock and vibration excitations to the system, such as in crashworthiness, gun recoil and seat suspension systems.



However, in high speed impact loading applications, the control strategy of the MRF damper is a significant factor in the performance of controllable damping to mitigate unwanted force. The available literature shows that most research on MRF damper and control performance has focused on noise and vibration attenuation, vibration absorption for large-scale buildings and related issues. Therefore, while discussion of control strategy of the MRF damper abounds, there are few studies on the control strategy of the MRF damper for an impact loading application. A few researchers, such as Hu et al. [20], have studied the control strategy of the MRF damper for an impact loading application. They invented a large-scale, single-ended MRF damper and developed a fuzzy logic controller capable of reducing recoil displacement by 40%. Bai et al. [14] developed a semi-active shock and vibration isolation system using an MRF damper and also invented a bidirectional-controllable mechanism using a skyhook control algorithm to improve shock and vibration performance. Bai & Wereley [13] studied the impact seat suspension for ground vehicles in a simulation analysis. They concluded that the proposed MRF damper can provide a larger damping force and wider dynamic range by using Optimal Bingham control.

Liu and Chen [21] designed a control strategy for the MRF damper for high-impact loads. In their research, a fuzzy proportional integral derivative (PID) control algorithm was developed, and the results significantly improved the system's dynamic performance under high impact damping conditions. Li and Wang [8] designed a full-scale gun recoil buffering system using an MRF damper and formulated an optimal control strategy with no feedback system (open-loop control). The study discovered that optimal control was better than passive control because it produces a smaller variation in recoil force. Fu et al. [22] invented a high viscosity MRF damper with a radial flow mode and design using a high viscosity linear polysiloxane magnetorheological fluid (HVLP MRF) as a control medium to produce excellent impact stability. Based on the literature, most of the research has focused on control strategy for MRF dampers used in impact applications. In summary, the control strategies for MRF dampers under impact loading that have been developed use a control algorithm with high computational cost. Such high computational cost can delay response of a control strategy, making it less viable in real-time applications. The present study seeks to formulate a simple control algorithm for the MRF damper for impact reduction control.

In the present study, MRF damper control characteristic performance is presented. First, MRF damper characteristics due to impact loadings are investigated using an impact pendulum test rig. The characteristics of the MRF damper are determined by applying various impact forces of the impact pendulum on the test rig. These characteristics data are used to generate a non-parametric model to represent MRF damper behaviour in MATLAB Simulink software using the adaptive neuro-fuzzy inference system (ANFIS) black box. The model is then used to design a simple controller, namely a fast, practical control (FPC) for the MRF damper. This controller is formulated for the MRF damper during impact by reducing the mathematical computational cost. In evaluating control strategy performance, a dynamic model of a single-degree of freedom (SDOF) impact isolation system is developed. The dynamic model is utilised in the controller development with the aim of reducing unwanted impacts such as jerk, acceleration and transmitted force.

This paper is organised as follows: The first section contains a brief introduction and summary of previous developments in control strategy for the MRF damper. Section two presents the modelling of an MRF damper. This is followed by a description of the proposed control strategy for the MRF damper due to impact loading application in Section three. Section four elaborates the experimental setup to measure the behaviour of the MRF damper. Section five discusses the simulation results to evaluate the effectiveness of the control strategy. Finally, Section six presents the conclusion and findings of this study.

2. Modelling of Magneto-Rheological Fluid Damper

The magneto-rheological fluid (MRF) was modelled by simulating its MRF damper characteristics using an interpolated multiple adaptive neuro-fuzzy inference system (ANFIS) approach. Detailed explanation to train ANFIS has been stated in Rahmat et al. [23]. To develop the mathematical model, the MRF damper was characterized using the impact pendulum test rig, considering various impact energies

produced by the pendulum mass and numerous values of constant input current. The physical figure for experimental instrumented characterization test rig is shown in Figure 1. Furthermore, the data obtained from experimental testing was then used to train ANFIS in predicting MRF damper behaviour. Three characterization data were used as model inputs for ANFIS training namely displacement, input current and impact energy. However, damping force was set as the model output in training data for the ANFIS toolbox in MATLAB Simulink software. Then, the ANFIS model was used in control strategy development to improve the performance of MRF damper. The training procedure has been stated in Rahmat et al. [23] and similar approach as proposed in [24-25].

3. Modelling of Impact Isolation System

Since the MRF damper is used to rapidly dissipate impact energy, a fast, practical control (FPC) controller is proposed in the present study. Fast, practical control is a practically and non-complex algorithm controller which is based on skyhook control combined with active force control (AFC) to improve stability and sustainability mechanical system performance of skyhook control. To evaluate the performance of the proposed controller, a single degree of freedom (SDOF) impact dynamics model of the MRF damper was formulated in the MATLAB Simulink simulation software. Figure 1 shows the SDOF model of the impact dynamics system for the MRF damper considered in this study.

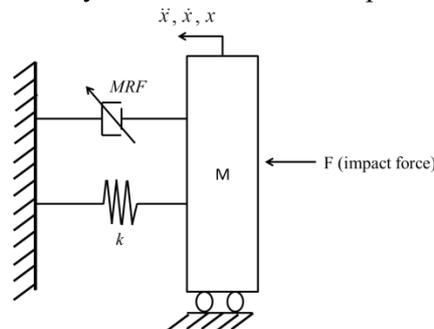


Figure 1. SDOF of impact dynamics system

According to the Newton's second law, the dynamic model can be derived as:

$$M\ddot{x} + MRF\dot{x} + kx = F_{impact} \quad (1)$$

where M is mass, k is the stiffness effect on the MRF damper, and MRF is the controllable damping force. The variables \ddot{x} , \dot{x} and x are acceleration, velocity and displacement of the mass, respectively. It should be noted that the damping force of the MRF damper is related to the magnitude of the current applied to the MRF damper and exhibits a time response for real time applications.

4. Control Strategy

In this study, the FPC is proposed to verify the impact reduction control performance for the SDOF impact isolation system as shown in Figure 2. The FPC controller is invented by combining skyhook and AFC controllers. These controller approaches were integrated to improve the force tracking performance of the MRF damper and to reduce the impact force to the body-impact isolation system. Therefore, each controller has an individual task to mitigate impact force. According to the mechanism of the skyhook control task, the damping force of the MRF damper should be adapted to pull down the mass since the relative velocity is positive. However, if the relative velocity is negative, the damping force pushes up the mass. AFC control assists skyhook control by providing better force-tracking control and using the output controller as the input for the current generator. This is accomplished through force estimation. Force estimation can be obtained from the force actuator by comparison to the force from

the impact isolation system. The governing equation for FPC based on skyhook control can be formulated as:

$$F = C_{sky} \times \dot{x} \tag{2}$$

Where F , C_{sky} and \dot{x} denote force sky, proportional gain and velocity of the system, respectively. Therefore, based on the general form of the skyhook control algorithm, the FPC control algorithm can be written as:

$$FPC = (C_{sky} \times \dot{x}) + F_e \tag{3}$$

where F_e represents force estimation. The proportional gain can be obtained through trial and error tuning methods, while the force estimation can be obtained by comparing the force actuator and the force of the system. Therefore, to estimate the force, the equation is derived as:

$$F_e = \frac{1}{k} (F_a - (Em \times \ddot{x})) \tag{4}$$

where k , F_a m and \ddot{x} denote a weighting function, force actuator, mass and acceleration of the impact isolation system, respectively. In the simulation analysis, the weighting function k and the estimated mass Em were obtained by trial and error method [26–28].

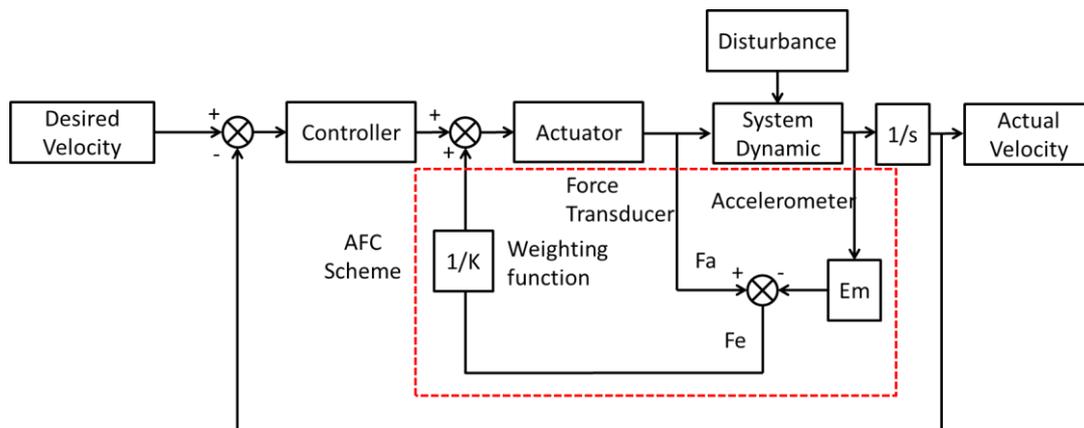


Figure 2. Schematic diagram of FPC

Table 1. Controller Parameter

Parameter	Value
C_{sky}	906
k	0.01
Em	0.2

5. Simulation Results

To analyse the performance of the MRF damper with FPC, the semi-active control response of the MRF damper was evaluated by considering with three different impact energies. The FPC control performance was then compared with the passive damper and the MRF damper controlled by skyhook control. Figure 3 presents the simulation results in term of jerk, acceleration and force in the time domain under low-impact, energy.

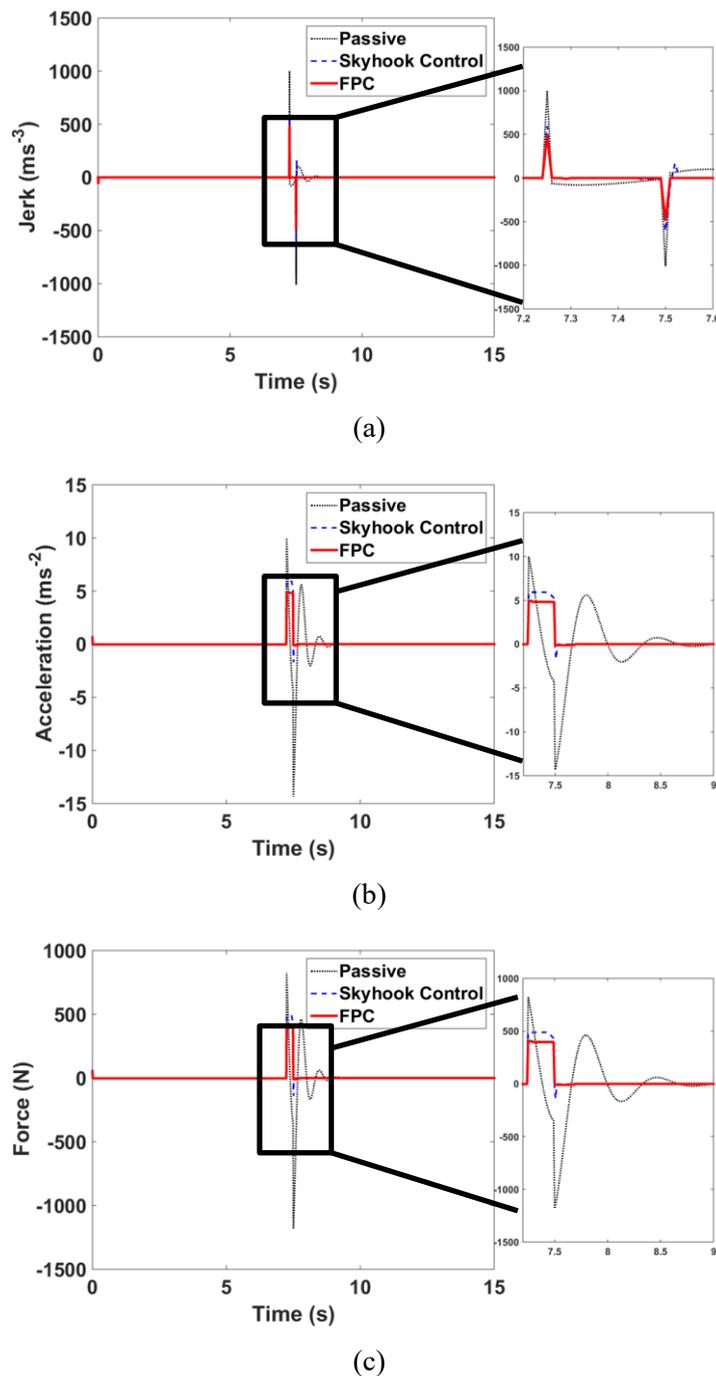


Figure 3. Simulation results under low impact energy (a) jerk response, (b) acceleration response and (c) force response

The simulation results shown in Figure 3 for the control performance of the passive damper, MRF damper controlled by skyhook control and FPC were evaluated and compared. The jerk response, acceleration response and force response of SDOF impact isolation are better in reducing impact energy using the FPC controller for MRF damper. The FPC controller reduced impact energy by 41% more than the passive damper. The MRF damper with FPC controller produced an acceleration response of 4.81 ms^{-2} , which is 18.7% reduction than skyhook control.

Next, the transmitted force of SDOF impact isolation by the MRF damper was demonstrated in Figure 3(c). The FPC controller showed by 18.7% greater effectiveness in acceleration reduction than the skyhook control. Since the controller performance was analysed with various impact energies, medium impact energy is considered in this study. The medium impact energy was used as simulation input for evaluation of the control strategy on the MRF damper performance. The analysis results under medium impact energy are illustrated in Figure 4.

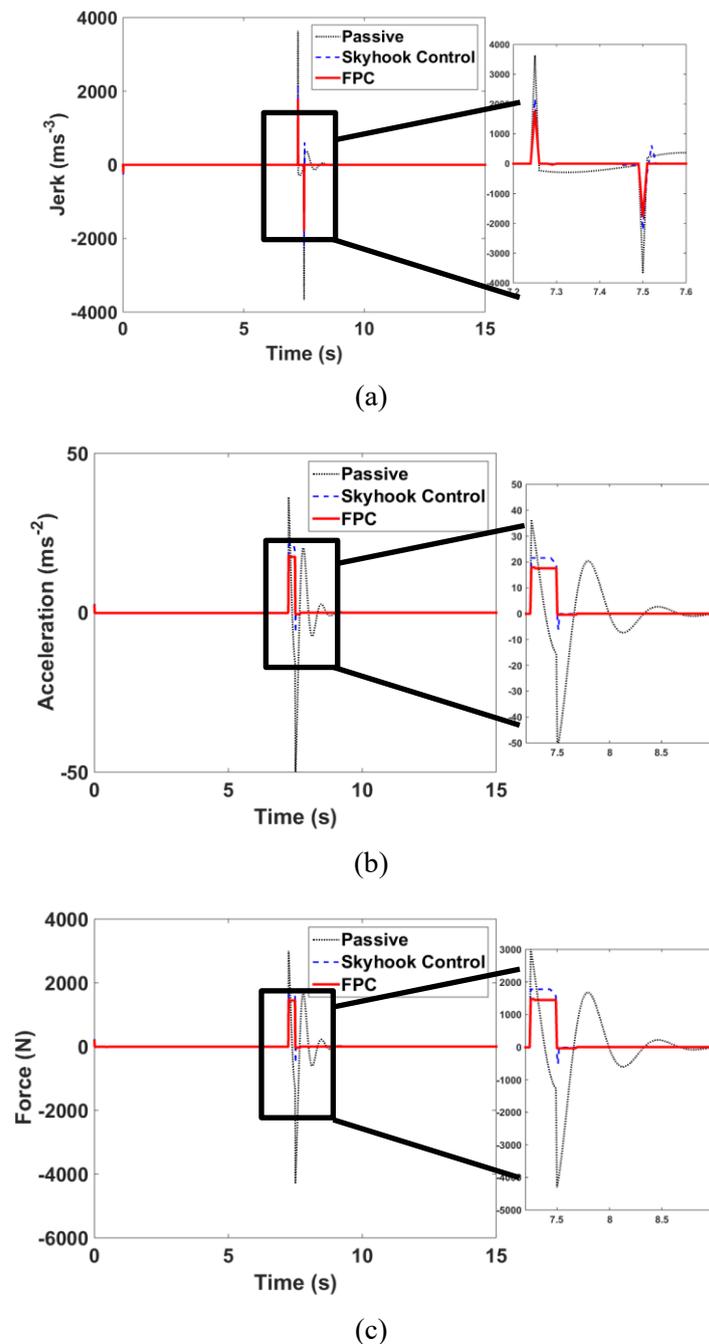
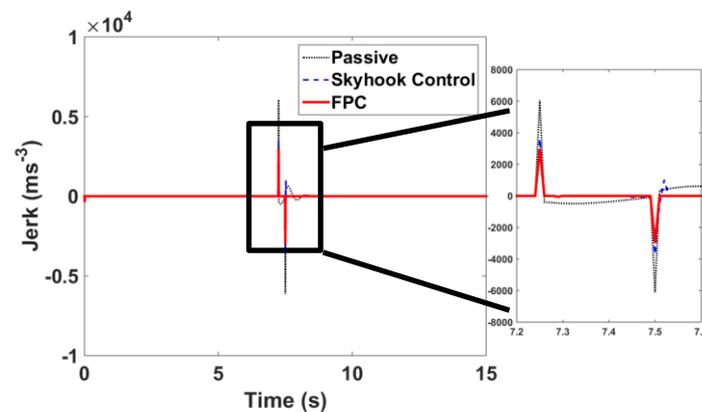


Figure 4. Simulation results under medium impact energy (a) jerk response, (b) acceleration and (c) force response

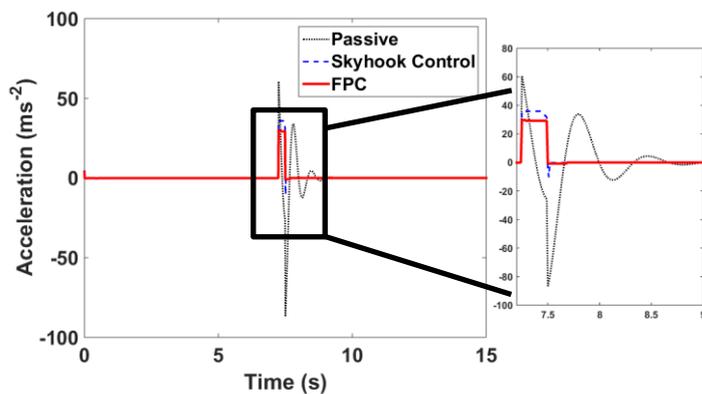
Based on these results, the performance criteria in term of jerk, acceleration and damping force of the SDOF impact isolation system were evaluated. Figure 4(a) shows the jerk response of the SDOF

impact isolation system in the time domain by comparing the performance of passive damper, MRF damper with skyhook control and FPC control. Under medium impact energy, the jerk response 2165ms^{-3} produced by MRF damper with skyhook control and 1796ms^{-3} produced by MRF damper with FPC controller. Based on that, the FPC controller has reduced 17.1% more than controlled by using skyhook control. The FPC controller exhibited good performance by providing input current to the MRF damper to produce damping force based on controller feedback. The acceleration response of the SDOF impact isolation system was substantially improved by the MRF damper control using skyhook control and the FPC controller.

The FPC controller provided the most stable of SDOF impact isolation system; it reduced acceleration by 18% as compared to the MRF damper controlled by the skyhook controller. The transmitted force was also analysed to measure the impact force that was dissipated by the MRF damper under medium impact energy. The FPC exhibited a better performance that the other approaches in force tracking. Next, the simulation results under high impact energy are indicated in Figure 5.



(a)



(b)

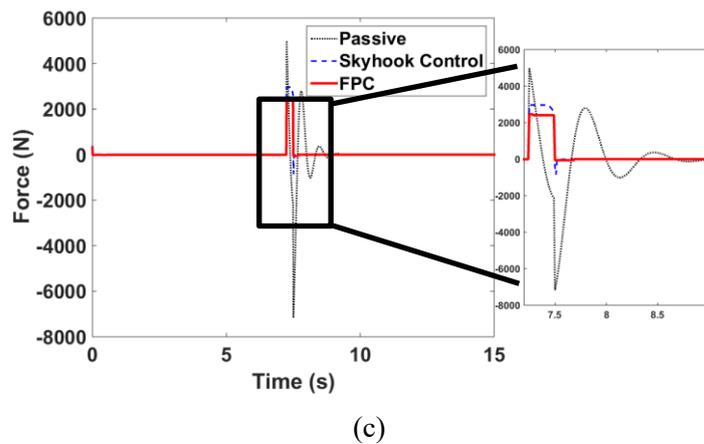


Figure 5. Simulation results under high impact energy (a) jerk response, (b) acceleration response and (c) force response

The results demonstrate the performance of the controller after being evaluated under high-impact energy. The responses of jerk, acceleration and transmission force SDOF impact isolation were used as the performance criteria to evaluate the effectiveness of the controller. As the results show, the passive damper was able to reduce the impact force; however, it needed a longer settling time to stabilize than the other control strategies. The MRF damper controlled by skyhook displayed in 0.8 s compared to other. The FPC tested in this analysis indicated better performance than that of the skyhook control. The FPC demonstrated a 0.35 s stabilization time while simultaneously reducing jerk, acceleration and transmitted force to the SDOF impact isolation system and achieving by 18.6% reduction in acceleration as compared with MRF controlled by skyhook control. The performance of improvement of control strategy based root mean square (RMS) peak to peak for impact reduction is summarized in Table 2, Table 3 and

Table 4.

Table 2. RMS analysis in term of jerk responses

Impact Energy		RMS (peak to peak)		Percentage improvement (%)
		Skyhook Control	FPC	
Low energy	impact	595ms ⁻³	495ms ⁻³	16.7%
Medium energy	impact	2165ms ⁻³	1796ms ⁻³	17.1%
High energy	impact	3598ms ⁻³	2994ms ⁻³	16.8%

Table 3. RMS analysis in term of acceleration response

Impact Energy		RMS (peak to peak)		Percentage improvement (%)
		Skyhook Control	FPC	
Low energy	impact	5.92ms ⁻²	4.81ms ⁻²	18.7%
Medium energy	impact	21.51ms ⁻²	17.50ms ⁻²	18.6%
High energy	impact	35.90 ms ⁻²	29.20 ms ⁻²	18.7%

Table 4. RMS analysis of force response

Impact Energy	RMS (peak to peak)		Percentage improvement (%)
	Skyhook Control	FPC	
Low impact energy	488.5 N	397.5 N	18.6%
Medium impact energy	1776.9 N	1445.7 N	18.6%
High impact energy	2961.5 N	2409.5 N	18.6%

6. Conclusion

The effectiveness of control strategies for impact reduction control in an MRF damper-based system was investigated in this study. Control performance of a passive damper, an MRF damper controlled by skyhook and an FPC were compared. Furthermore, a mechanical system model of SDOF impact isolation systems using an MRF damper with different controllers was constructed. The governing equation for SDOF impact isolation system was derived. An FPC control algorithm with less computational intensity was formulated and used to verify the impact reduction control performance of the systems through simulation. The control performance of the impact isolation systems under impact loading due to various horizontal impact energies was evaluated. Various impact energies were considered in this analysis for evaluating the capability of the controller to adapt to various inputs. Based on the results of the simulation analysis, the FPC demonstrated better control performance for the MRF damper, achieving 18.7% more reduction in acceleration than the skyhook control for SDOF impact isolation system.

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