FRACTIONAL ORDER CONTROL FOR POUNDING MITIGATION IN MULTI-SPAN BRIDGES USING MR DAMPERS

O. El-Khoury¹, J. Hur², and A. Shafieezadeh³

ABSTRACT

Seismic-induced pounding between adjacent structures such as neighboring bridge deck segments have detrimental impacts on the extent of damage to structures and can potentially lead to collapse. Magnetorheological (MR) dampers are popular semi-active devices that exhibit desirable features such as robustness, stability, adaptability and low power requirements as compared to passive and active systems. The objective here is to propose a control methodology that can effectively utilize MR Dampers to attenuate pounding in adjacent structures while minimizing other key responses of interest. For this purpose, a fractional order sliding mode controller is developed, where the control force is divided into two components involving a sliding mode controller with the sliding surface designed using linear quadratic regulator, and a fractional order control term.

The proposed semi-active control algorithm is applied to a three-span bridge on nonlinear rubber bearings. This control design is tested using shake table tests of the three-span bridge subjected to scaled Kobe ground motions. The MR dampers are set to minimum and maximum current values, and the optimal current determined using the proposed semi-active strategy. The results for the semi-active controller case show noticeable improvements in some of the critical displacement, acceleration and pounding responses over controlled and passive-off cases. Findings of this study reveal the potential of fractional order controllers for seismic response mitigation of structures.

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Fractional Order Control for Pounding Mitigation in Multi-Span Bridges Using MR Dampers

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Seismic-induced pounding between adjacent structures such as neighboring bridge deck segments have detrimental impacts on the extent of damage to structures and can potentially lead to collapse. Magnetorheological (MR) dampers are popular semi-active devices that exhibit desirable features such as robustness, stability, adaptability and low power requirements as compared to passive and active systems. The objective here is to propose a control methodology that can effectively utilize MR Dampers to attenuate pounding in adjacent structures while minimizing other key responses of interest. For this purpose, a fractional order sliding mode controller is developed, where the control force is divided into two components involving a sliding mode controller with the sliding surface designed using linear quadratic regulator, and a fractional order control term.

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\textbf{Introduction}

Structural control methods including active, semi-active, and hybrid systems have been shown to enhance structural performance both numerically and experimentally. Semi-active control systems requiring a small source of power to adjust mechanical properties of the control device provide reliable energy dissipation mechanisms that possess the adaptability of active control systems. Magnetorheological (MR) dampers are a class of semi-active devices that utilize MR fluids to provide a controllable yield force that monotonically increases with the applied magnetic field. MR dampers have attracted great attention in seismic response mitigation of civil structures since

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a large number of investigations showed the promising performance of such devices [1].

Numerous control strategies have been proposed to mitigate responses of dynamical systems subjected to external disturbances or to track reference commands. Among them, are fractional order controllers (FOC) that are referred to a class of controllers that utilize fractional order operators as a part of their structure. Fractional order operators correspond to the non-integer orders for differential and integral operators. Recently, fractional order calculus has found many applications in different fields such as material modeling, theory of fractals, theory of control of dynamical systems, biological systems, and signal processing. The satisfactory performance of FOC in disturbance rejection and reference command tracking has been demonstrated in several investigations [3-4]. Another class of rather conventional controllers are sliding mode control (SMC) methods that have desirable robustness performance. However, the objective of the SMC algorithm is not to optimally minimize the response of the system, such as that in conventional optimal feedback control methods, but rather mitigate it in a manner that preserves the stability of the system. Moreover, the design of the sliding surface is a subjective procedure that relies heavily on the experience of the designer. The authors previously addressed these limitations and validated the performance of the algorithm for a seismically-excited multi-span bridge [5-7].

This paper proposes a control strategy involving fractional order sliding surfaces called fractional sliding mode control (FSMC) method in order to integrate desirable features of sliding mode control with fractional order calculus. The proposed semi-active control algorithm is analyzed and tested using shake-table tests on a three-span bridge elaborated in [5]. The nonlinear bridge was modelled and further stochastically linearized for control design and optimization [5]. Subsequently, clipped-optimal FSMC is designed by employing an optimization procedure to determine the weighing matrices. Scaled Kobe ground motions are used to evaluate the performance of the structure and control systems including passive off, passive on, and semi-active control strategies. The results are elaborated for small and large scaled Kobe (KB) earthquake ground motions at different controlled states: uncontrolled, passively controlled, and semi-actively controlled structure.

**Fractional Sliding Mode Control**

In this section, a state-space based FSMC is initially derived for the active control of a fully observable system. Then, the considerations of semi-active control and partial observability are accounted for in the design implementation for the particular system that is explained later in the paper. A general system subjected to stochastic disturbance is represented in state-space model as

\[
\dot{X} = f(X, u) = A_{\text{state}}X + Bu + F_e
\]

where \(X\) is the response vector and \(A_{\text{state}}\) is called the system matrix which is derived using mass, damping, and linear and nonlinear stiffness components of the dynamic system. In addition, the system matrix can include the dynamics of the control device and the nonlinear components of the system model. In Equation (1), \(F_e, u, \) and \(B\) represent the excitation vector, control vector, and the location matrix of controllers, respectively. In control design, the SMC algorithm is not based on a minimization procedure such as conventional feedback methods. However, the SMC design is known to be a two-step procedure. The first step involved the sliding surface design. Then, a control law is selected to drive the response variables to the defined sliding curve. In that respect, the sliding surface, \(S\) is divided into a linear component and fractional component represented as
\[ S = \sigma_1 X + \sigma_2 d^\alpha X/dt^\alpha \]  

where $\sigma_1$ and $\sigma_2$ is a constant sliding surface weighted matrices for linear and fractional components respectively. The parameter, $\alpha (0,1)$, is a real number that denotes the fractional differential of the state space vector. In the sliding surface design, the linear component, $\sigma_1 X$, is designed according to the method presented in [8], Then, the fractional component, $\sigma_2 d^\alpha X/dt^\alpha$, is imposed and optimized through second level optimization, defined later. Substituting Equation (1) in Equation (2), the time differential is rearranged to:

\[ \dot{S} = \sigma_1 (A_{\text{state}} X + Bu + F_e) + \sigma_2 d^{\alpha+1} X/dt^{\alpha+1} \]  

Equating Equation (3) to zero, the optimal control force is represented as

\[ u = - (\sigma_1 B)^{-1} (\sigma_1 (A_{\text{state}} X + F_e) + \sigma_2 d^{\alpha+1} X/dt^{\alpha+1}) \]  

Since the external response, $F_e$, is not stochastic (unknown priori), the control equation can be synthesized implicitly via discontinuous control defined in terms of the known system parameters. Therefore, the term, $F_e$, is dropped and instead through a properly selected parameter, $\mu (\geq 0)$, where the reachability of the sliding mode is guaranteed with the condition of $SS \leq 0$ [9]. Consequently, the control SMC force is estimated to be

\[ u = \sigma - \mu \text{sat}(S) \]  

where $\sigma$ is defined as $-(\sigma_1 B)^{-1} (\sigma_1 (A_{\text{state}} X) + \sigma_2 d^{\alpha+1} X/dt^{\alpha+1})$. In the controlled system in Equation (1), the measured responses are used to estimate the state vector through an observer model.

**Shake Table Test Results**

The proposed control methodology is applied to a three-span bridge equipped with two semi-active MR dampers attached between adjacent spans. The overall length of the spans is 10.6 m, and the bridge is equipped with two MR dampers attached between adjacent spans. The bridge model includes three reinforced concrete decks, each supported by four rubber bearings, as shown in Figure 1. The dimensions of the bridge are given in the longitudinal and top views in Figure 1. In this setting, the four supports of span A and the two left supports of span B are positioned on shake-table A, while the two right supports of span B and the supports of span C are placed on shake-table B. To suppress the extreme effects of seismic pounding, two MR dampers are installed between adjacent spans. The ground motion is scaled to 20% (KB20), 40% (KB40), and 50% (KB50) and four cases are considered: uncontrolled, passive-off and passive-on where the current is set to minimum and maximum, respectively, and the semi-active control where the optimal current is determined using the FSMC strategy.
Prior to control design, the bridge components including rubber bearings, lead-rubber bearings, and the semi-active device and the pounding phenomenon are modelled and experimentally calibrated and validated [5-7]. Bouc Wen model [10] is used to characterize the nonlinear hysteretic behavior of rubber bearings and the current dependent nonlinear behavior of MR dampers. Damped Hertz Impact model [11] is adopted to capture pounding behavior between adjacent spans and between end spans and the abutments. Rubber bearing and lead-rubber bearing models of the spans are calibrated individually under El-Centro ground motion. Models for pounding between adjacent bridge components are calibrated subsequently using the full uncontrolled bridge model for high intensity ground motions that induced pounding. The MR damper model is calibrated based on harmonic tests. The calibration process is performed using global optimization method [12] to minimize an error cost function between the experimental data and simulation results. The aforementioned models are validated for tests other than those used in the calibration process [5-7].

In order to analyze the performance of uncontrolled, passive-off, passive-on, and the proposed semi-active controller cases, the bridge system is subjected to scaled Kobe ground motion. This record corresponds to 1995 Kobe Earthquake with Mw of 6.9 recorded at the KJMA observatory station with a distance to fault rupture of 0.6 km. This was a near-field event and the record included high amplitude long period velocity pulses with a peak ground acceleration (PGA) of 0.821 g. The uncontrolled case does not include MR dampers between adjacent spans, while in passive-off and passive-on cases the input current to the MR dampers is set to minimum and maximum, respectively. For the case of semi-active control, the optimal current is determined using the FSMC strategy.

Shake table test results for all control cases and scaled Kobe ground motions are presented in Table 1. The time history of displacement and acceleration responses of spans A and C for KB50 are plotted in Figures 2a-d. Under KB20, no pounding is observed in all cases; however, passive and semi-active cases showed notable reductions in critical relative displacements compared with the uncontrolled case (e.g. critical displacement $x_{12}$ reduced to 72%, 31%, and 39% of the uncontrolled systems for passive-off, passive-on, and semi-active cases, respectively). Seismic pounding can be detected by large acceleration spikes in the response of the spans as shown in Figures 2c-d. For KB40, no spikes are observed for passive-on and semi-active cases, while 7 and 6 acceleration spikes are observed for uncontrolled and passive-off cases, respectively. Results indicate that both passive-on and semi-active cases yield considerable improvements over the uncontrolled case as shown in Table 1. For example, the relative displacement $x_{12}$ is reduced by 10.5%, 35%, and 32.5% using passive-off, passive-on, and semi-active control strategies, respectively, compared to the uncontrolled bridge.
For KB50, the passive-off (zero current) case was not considered to avoid potential damage to the MR dampers. For this scaled ground motion, significant pounding is observed between adjacent spans in the uncontrolled state. Nevertheless, no acceleration spikes are observed for the semi-active and the passive-on cases. As for the semi-actively controlled system, a significant improvement is gained compared to the uncontrolled state especially for relative displacements, $x_{12}$ and $x_{23}$ where the semi-active controller reduced these responses by 27% and 29%, respectively (see Table 1). The passive-on state has the largest improvements, where 29% and 28% reductions in the relative displacements, $x_{12}$ and $x_{23}$ are observed compared to the uncontrolled state.

Table 1. Results for three-span bridge.

<table>
<thead>
<tr>
<th>KB40</th>
<th>Critical/Peak displacements (mm) and peak accelerations (g)</th>
<th>RMS of displacements (mm) and accelerations (g)</th>
<th>Current / Energy Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>$x_1$</td>
<td>$x_{12}$</td>
<td>$x_{23}$</td>
</tr>
<tr>
<td>Uncontrolled</td>
<td>18.56/13.62</td>
<td>28.88/28.88</td>
<td>30.31/30.3</td>
</tr>
<tr>
<td>Passive-off</td>
<td>11.79/10.73</td>
<td>25.99/25.99</td>
<td>29.00/29.00</td>
</tr>
<tr>
<td>Passive-on</td>
<td>11.22/8.72</td>
<td>18.94/15.70</td>
<td>19.43/19.43</td>
</tr>
<tr>
<td>FSMC</td>
<td>12.92/10.10</td>
<td>19.57/16.35</td>
<td>20.83/20.83</td>
</tr>
</tbody>
</table>

Table 1. Results for three-span bridge.

<table>
<thead>
<tr>
<th>KB50</th>
<th>Critical/Peak displacements (mm) and peak accelerations (g)</th>
<th>RMS of displacements (mm) and accelerations (g)</th>
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<tbody>
<tr>
<td>State</td>
<td>$x_1$</td>
<td>$x_{12}$</td>
<td>$x_{23}$</td>
</tr>
<tr>
<td>Uncontrolled</td>
<td>16.65/12.45</td>
<td>27.79/27.79</td>
<td>29.38/29.38</td>
</tr>
<tr>
<td>Passive-on</td>
<td>12.06/10.22</td>
<td>19.94/16.6</td>
<td>21.08/21.08</td>
</tr>
<tr>
<td>FSMC</td>
<td>13.14/9.91</td>
<td>21.28/18.08</td>
<td>21.13/21.13</td>
</tr>
</tbody>
</table>
Moreover, one of the main advantages of the control algorithm is providing a performance close to that of passive-on but with a lower energy consumption. Under KB50, the mean of the current used in the MR damper between spans A and B (MR-AB) and between spans B and C (MR-BC) is reduced to 78% and 71% of passive-on, and the energy consumptions in these MR dampers are reduced further to 39% and 35% of passive-on state. Similar results are observed for KB40, where the power consumption is reduced by at least 21% compared to the passive-on case. Adding MR dampers shows noteworthy improvement and enhances the energy dissipation capabilities of the system especially for ground motions with large PGA.
Conclusions

In this paper, the effectiveness of MR dampers controlled using passive and semi-active strategies are examined for response reduction and in particular pounding mitigation of adjacent structures. The damper is set at zero current, maximum current, and an optimal current value that is determined through a semi-active control strategy. For semi-active control, the performance of the system converges to that of the passive-on state with a considerable reduction in the energy consumption (e.g. 30% reduction in critical displacements of fractional sliding mode control (FSMC) case compared with uncontrolled case and a reduction in energy of 62-65% compared with passive-on). In addition, no pounding is observed in the passive-on and FSMC cases.

Results presented here indicate that installation of MR dampers between adjacent structures has the potential to reduce damage due to pounding and excessive gap openings in addition to mitigating other critical structural responses. The proposed FSMC semi-active control method provides very close performance to the passive-on case but with a considerably reduced energy consumption during the seismic activity. Implementation of these passive and semi-active strategies can significantly reduce the likelihood of pounding, damage, and collapse, and therefore can enhance the resilience of bridges and keep them operational following moderate and large seismic events.

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References


