Seismic Control of Highway Bridges using Fuzzy Logic Control

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Abstract

Investigation of past years shows seismic pounding between successive bridge segment which is usually only of a few centimeters resulting significant structural damage. The aim of this paper is to investigate the possibility of using semi-active control systems such as magnetorheological (MR) damper to reduce the impact between the adjacent segments of the highway bridges in severe seismic event. In this study, a highway bridge with five segments is evaluated numerically for semi-active control system by installing MR dampers in between adjacent girders. Fuzzy logic control strategy is used as control algorithm to command MR damper. The structural response parameters such as displacement, acceleration and pounding force are evaluated for controlled and uncontrolled bridge using MATLAB (SIMULINK) under earthquake excitations. The results show that semi-active control strategy using fuzzy logic controller reduces the acceleration response and pounding force of adjacent bridge deck in a highway bridge.

Keyword- Earthquake, FLC, Highway Bridge, Simulation, MR Damper

I. Introduction

Ever since the existence of the mankind it has been noticed that there is a great change occurs in the field of bridge engineering and technology. In the field of bridge engineering, there are some unobserved problem of bridge pounding and unseating of bridge girders arises during special variation of earthquake ground motion. This problem arises because of the insufficient separation distance between successive bridge decks which is usually only of a few centimeters. Hence, it is not sufficient to prevent pounding phenomenon between successive bridge segments.

During the extreme earthquake in past several decades, it has been observed that velocity interchange between adjacent superstructures during pounding will instantaneously increase the acceleration of superstructures. Also, collision between adjacent bridge segments will generate tremendous addition impact forces to the structural members, this arise in spalling of concrete and damages to the piers and abutments, even its consequence in unseating of bridge girders also. Many interrogations on pounding between adjacent bridge segments have been accomplished. Major works focus on how to determine proper separation distance to avoid pounding effect and to lighten unseating of bridge deck by using possible reduction measure. Many researchers have focused on MR damper as a semi-active control system to reduce the pounding effects along with different control algorithms. In this study, to find the possible route to improve the performance of bridge decks and girder against exceptional earthquake ground motion to reduce pounding effects using Magnetorheological damper as semi-active control device.

II. Problem Formulation

A. *Assumption and Limitation*

To make the problem feasible and clarify the analysis, some assumption related to the earthquake excitation and structures are necessary and given before the analysis.

In this study are only concentrated on the highway bridges with base-isolated rubber bearings. For this kind of bridges, the stiffness of the piers is remarkably larger than that of the rubber bearings. The offering of the dynamics of the piers to the total responses of the superstructure segments is comparatively small and can be neglected to more focus the analysis on the fundamental characteristics of the pounding problem. Moreover, the superstructure segments of the bridges are assumed to be symmetrical with their symmetric planes in alignment. Asymmetric highway bridges with torsion are not labeled here.

The ground motion of the earthquake excitations is assumed to be the longitudinal direction of the bridges. The multi-supported ground motion, which induces in series movements and consequently, results the collisions between the adjacent superstructure segments, is included by taking the wave propagation outcome of the earthquake excitations into consideration. the prescribed ground motion is assumed to be equivalent at each support, but it is not applied at the same moment. The first pier along the wave propagation direction is assumed to be experienced a specified ground motion, and the motion at the other following supports is delayed based on the distance between the adjacent supports and the speed of the L-wave of a typical earthquake.

B. Contact-Element Model of Collision between Adjacent Superstructures

Pounding between the decks of highway bridges is a complex nonlinear process. Accurately analysis of seismic pounding of the bridges is difficult and unnecessary for engineering analysis. The former stereo mechanical approach is to computer the after-impact velocities of colliding masses complying with the impulse-momentum law based on the rigid body assumption of the bridge decks (Goldsmith 2001). The contact-element approach, which is used in the pounding analysis of this study.

The illustrative diagram of the contact-element model of impact between the adjacent segments of highway bridges is shown in Figure 1. According to the model, the longitudinal collision between the (i-1)th and the ith superstructure segments is modeled as an elastic spring with stiffness of $k_{p,i}$ and a damping coefficient of $c_{p,i}$ in parallel coupled a gap with spacing of d_i in series. The adjacent segments move self-sufficiently during earthquakes except for the case when the relative displacement between the ith and (i-1)th segments is larger than the gap size d_i. The contact constraint of the collision between the adjacent segments is then written as displacements of the adjacent superstructure segments with respect to the ground, respectively. The impact force, $f_{p,i}(t)$, at the ith expansion joint during collision is thus given as

$$f_{p,i}(t) = k_{p,i}(t)\delta_{i-1}(t) + c_{p,i}(t)\dot{\delta}_{i-1,i}(t)$$

C. Governing Equation of Motion

Study a base-isolated highway bridge with several superstructure segments. Based on assumptions as defined above, each segment of the bridge is modeled as a linear independent single-degree-of freedom system with lumped mass. For a bridge with n superstructure segments and two abutments, as shown in Figure 1.

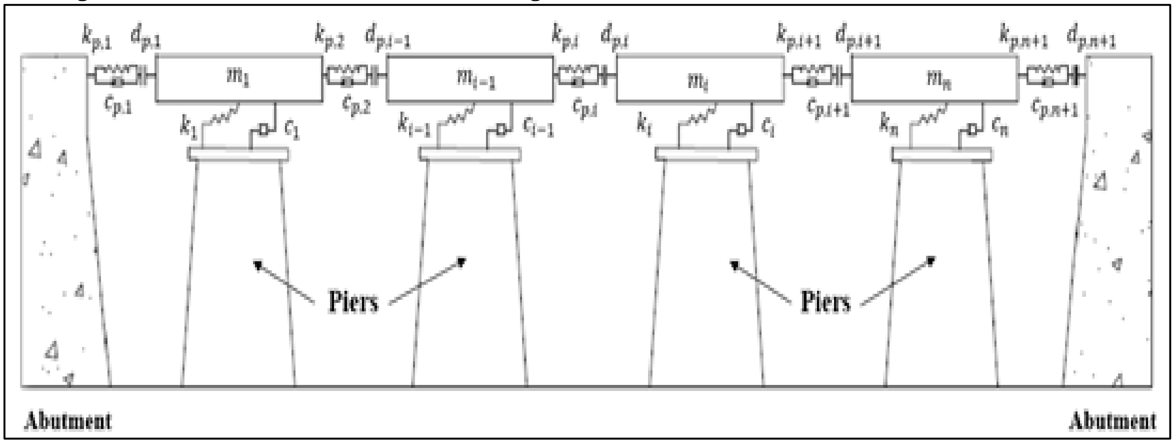


Fig. 1: Analytical Model of the Bridge with Pounding Effect the analysis

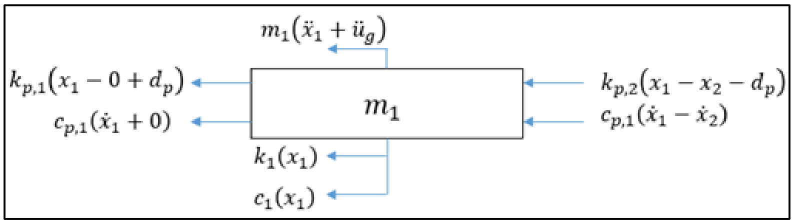


Fig. 2: Free body diagram of a 1st deck

In this study, we have total five decks and each deck we solved using free body diagram as show in Figure 2 and then we have total five equation of each decks. By using the matrix-vector notation the governing equation of motion of the structure in longitudinal direction with pounding effects can be written as:

$$M\ddot{X}(t) + [C + C_p(t)]\dot{X}(t) + [K + K_p(t)]X + E_p(t)d_p + F_d = -M\ddot{u}_g(t)$$

To reduce the pounding between the adjacent superstructure segments, control devices are assumed to be installed in the highway bridge. MR damper are placed between two decks. In order to validate the developed simulation program of the structure control method describe in “Pounding Reduction of Highway bridges with Pounding Effect by Using Magnetorheological Damper Under Earthquake Excitations” by Anxin Guo et al. (2008) is used.

Where, $X(t)$, $\dot{X}(t)$ and $\ddot{X}(t)$ are the displacement, velocity and acceleration vectors, M is the mass matrix of the superstructure segments, C and K are the damping and stiffness matrices due to rubber bearings, $C_p(t)$ and $K_p(t)$ are the damping and stiffness matrices due to structural pounding, $\ddot{u}_g(t)$ is an acceleration vector in the longitudinal direction considering the wave propagation. $E_p(t)$ is the matrix of pounding forces, d_p is the vector of the gap size. F_d is the damper force. Above Equation is converted in to state space formulation and then simulation have been carried out in MATLAB for five segmented isolated highway bridge for Uncontrolled and Controlled system.

D. Dynamic Behavior of MR Damper

Bouc-wen model for MR damper is studied. The phenomenological model proposed by Spencer, B.F. et al., 1997 represented the modified hysteresis model for MR damper as presented below. Force produced by this model is,

$$F = c_1 v_d + k_1(x - x_0)$$

Where, v_d is given by, $v_d = \frac{1}{(c_0+c_1)}\{\alpha_0 z + c_0\dot{x} + k_0(x - y)\}$

$$\dot{z} = -\gamma|\dot{x} - v_d|z|z|^{n-1} - \beta(\dot{x} - v_d)|z|^n + A_m(\dot{x} - v_d)$$

Where, y is the Displacement of the damper, c_1 is the Viscous damping for roll-off at low velocities, v_d is the Velocity of the damper, α_0 is the Evolutionary coefficient, x_0 is the Initial displacement of spring k_1, k_1 is the Accumulation stiffness, k_0 is the Stiffness at large velocities, x is the Internal pseudo-displacement of the damper, z is the evolutionary variable, c_0 is the Viscous damping at large velocities and γ, β, n and A_m is the Shape parameters of the hysteresis loop.

E. Fuzzy Control of MR Damper

The input variables were relative displacement (d) and velocity (v) of between each deck of highway bridge at which MR damper are placed, which were defined on the universes of discourse $[-d_{max}, d_{max}]$ and $[-v_{max}, v_{max}]$, respectively while the output was selected as the applied current $[-i_{max}, i_{max}]$. For the input membership function, seven identical triangles with 50% overlay were defined on the regulated universe of discourse [-1,1], as shown in figure 6(a). For the output, four identical triangles, also with 50% overlay were defined on the universe of discourse [0,1], and presented in figure 2.

To stabilize input variable, scaling factors k_v and k_d were employed for velocity and displacement, respectively. Since the output universe of the discourse was also normalized, a scaling factor, k_u is essential. Because scaling factors are responsible for mapping inputs and outputs to universes of discourse, they have a large effect on controller's performance. Selection of these factor is therefore of the utmost importance and was based on results of a parametric analysis.

To select the best values for k_d, k_u and k_v, a parameter analysis was performed was performed, and several values ranging from 0 to 50 were considered for k_d and k_v.

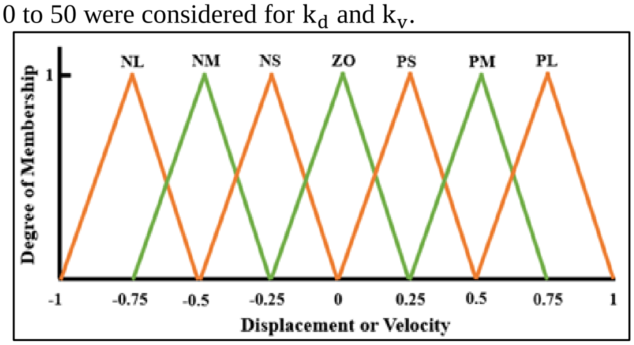


Fig. 3 (a): Input Membership Function

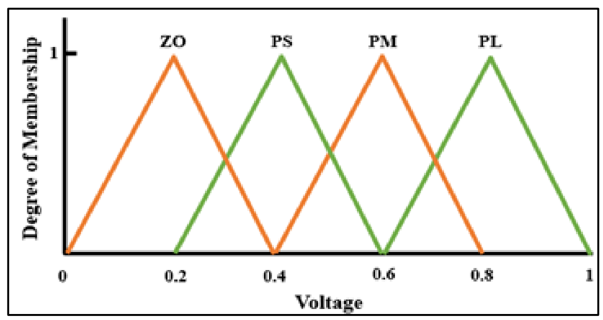


Fig. 3 (b): Output Membership Function

D\V	*NL*	*NM*	*NS*	*ZO*	*PS*	*PM*	*PL*
NL	*PL*	*PL*	*PL*	*PM*	*ZO*	*ZO*	*ZO*
NM	*PL*	*PL*	*PL*	*PS*	*ZO*	*ZO*	*PS*
NS	*PL*	*PL*	*PL*	*ZO*	*ZO*	*PS*	*PM*
ZO	*PL*	*PM*	*PS*	*ZO*	*PS*	*PM*	*PL*
PS	*PM*	*PS*	*ZO*	*ZO*	*PL*	*PL*	*PL*
PM	*PS*	*ZO*	*ZO*	*PS*	*PL*	*PL*	*PL*
PL	*ZO*	*ZO*	*ZO*	*PM*	*PL*	*PL*	*PL*

Table 1: Control Rule Base (liu Y et al 2001)

These include values obtained with equations proposed by Liu et al. (2001):

$$k_d = \frac{3}{d_{max}} \ , \ k_v = \frac{3}{v_{max}}$$

In these equations d_{max} and v_{max} refer to the maximum displacement and velocity, respectively. These quantities were estimated based on the largest uncontrolled responses of the uncontrolled structure to the following earthquakes: Kobe, Northridge and EL Centro. Value for k_u are suggested by Liu et al. (2001): The inference rules for calculating the desired input current to the MR damper are existing in Table 1.

$$k_u = \frac{i_{max} - i_{min}}{3}$$

NL= Negative large, NM= Negative medium, NS= Negative small, ZO= Zero, PS= Positive small, PM= Positive medium, PL=Positive large

III. NUMERICAL STUDY

Numerical study is carried out using analytical model of the highway bridge for Controlled and Uncontrolled system under consideration for calculation of response quantities: pounding force and acceleration. The parameter of Isolated Highway Bridge is taken from the paper of Anxin Guo - "Pounding Reduction of Highway bridges with Pounding Effect by Using Magnetorheological Damper Under Earthquake Excitations". Simulation is prepared in MATLAB SIMULINK 2016 using Fuzzy logic controller for five segmented isolated highway bridge using MR damper placed between adjacent girder. Each segment is 3@40m long and 14m wide. The total mass of a segment is 2400 ton. The effective stiffness and equivalent damping ratio of the rubber bearings of each pier are designed to be 2.3298×10^7 N/m and 0.14 respectively. The natural frequency of the superstructure in longitudinal direction is 1.164s, Gap size of 0.05m is considered. The damping coefficient and contact stiffness are calculated to be 1.808×10^7 Ns/m and 3.475×10^9 N/m, respectively, based on the structural properties of the bridge. The Earthquake ground motion considered for the study are 1979 Imperial Valley earthquake (PGA= 0.35g and 0.61g) recorded at Delta and EL Centro Array #8 station, respectively; 1995 Kobe earthquake (PGA= 0.35g and 0.83g) recorded at Kakogawa and KJMA station, respectively; 1989 Loma Prieta earthquake (PGA= 0.33g and 0.57g) recorded at CA-Airport and LGPC station, respectively; 1994 Northridge earthquake (PGA= 0.21g and 0.58g) recorded at 116th St. School and Newhall station, respectively.

The parameter of MR damper is taken from the paper Shrimali – "Seismic response analysis of coupled building involving MR damper and elastomeric base isolation".

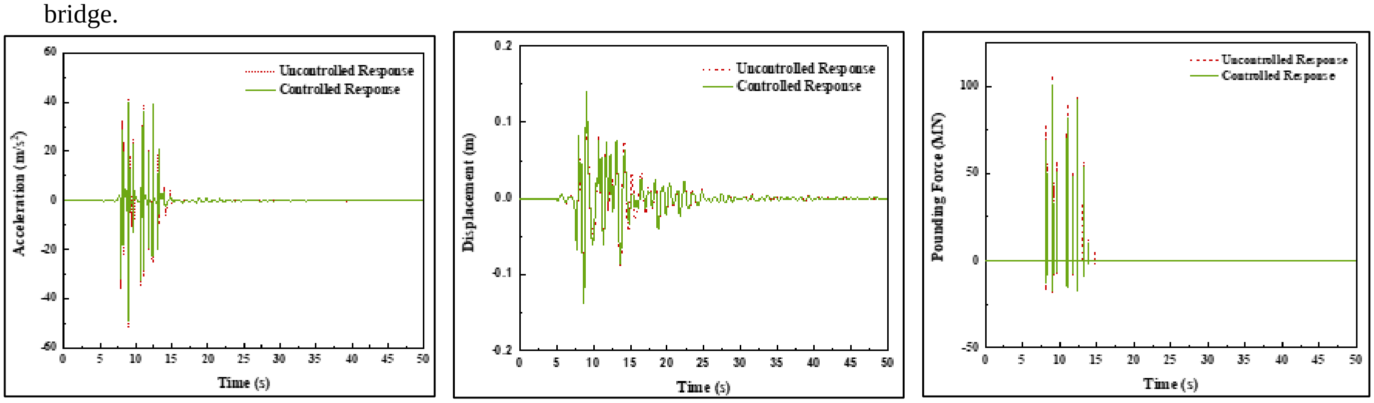
The MR damper parameter used in this study of 600 kN force capacity are: a_{0a} = 8.70 kN/m, a_{0b} = 6.40 kN/m/V, C_{0a} = 50.30 kN.s/m, C_{0b} = 48.70 kN.s/m/V, C_{1a} = 8106.20 kN.s/m, C_{1b} = 7807.90 kN.s/m/V,
A_d = 810.50, γ = 496 m^{-2}, β = 496 m^{-2}, η = 195 sec^{-1}
k_0 = 0.0054 kN/m, k_1 = 0.0087 kN/m, x_0 = 0.18 m, n = 6.

Segment 3 in the middle of the highway bridge is selected as the analysis object. Figure 4 shows the responses of the bridge for the Kobe earthquake recorded at far fault when pounding is included in the analysis. It can be seen form the Figure that pounding force for uncontrolled and controlled are 16.37 MN and 0 MN respectively.

IV. CONCLUSION

A highway bridge with five segments is evaluated numerically for semi-active control system by installing MR dampers in between adjacent girders. Fuzzy logic control algorithm is working for semi-active controller design. Form the results of present study, the following conclusions can be drawn.

- The acceleration response between adjacent bridge segments reduce up to 70% in semi-actively controlled bridge using FLC compared to uncontrolled bridge with a slight increase in displacement.
- The pounding force of semi-actively controlled bridge using FLC is greatly reduces by 5 to 100% compared to uncontrolled bridge.



(a) (b) (c)

Fig. 5: (a) Absolute Acceleration Response (b) Displacement Responses (c) Pounding force on right side of Bridge Segment 3 for controlled and uncontrolled system (segment 3 under Near-fault Kobe earthquake)

Earthquake	*Displacement (m)*		*Absolute Acceleration (m/s^2)*		*Pounding Force (MN)*	
	Uncontrolled	*Controlled*	*Uncontrolled*	*Controlled*	*Uncontrolled*	*Controlled*
Far-fault ground motion						
1979 Imperial valley, Mexico	*0.086*	*0.081*	*19.12*	*17.38*	*45.28*	*40.67*
1995 Kobe, Japan	*0.062*	*0.066*	*7.44*	*2.06*	*16.37*	*0*
1989 Loma Prieta, San Francisco	*0.065*	*0.063*	*12.43*	*8.48*	*28.84*	*18.73*
1994 Northridge, Los Angeles	*0.026*	*0.024*	*0.82*	*0.80*	*0*	*0*
Near-fault ground motion						
1979 Imperial valley, California	*0.089*	*0.090*	*11.35*	*10.25*	*26.07*	*21.65*
1995 Kobe, Japan	*0.137*	*0.139*	*51.48*	*48.75*	*106.40*	*101.17*

1989 Loma Prieta	*0.134*	*0.137*	*39.12*	*36.86*	*95.66*	*88.63*
1994 Northridge	*0.088*	*0.085*	*36.63*	*34.65*	*86.68*	*81.54*

Table 2: Comparative Structural response of an isolated bridge under different Ground Motion

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