Fuzzy Control Strategy for Vibration Isolation of Bridge Based on Magneto-rheological Bearing

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Keywords: Bridge engineering, Simply supported bridge, MRB, Earthquake, Fuzzy control

Abstract. As the weakest part of the bridge system, traditional bridge bearing is incapable of isolating the heavy load such as earthquake. The developed Bouc-wen model is firstly used to represent the constitutive relation and force-displacement behavior of MRB. Then, the lead rubber bearing (LRB), passive magnetorheological elastomer bearing (MRB) and controllable MRB are modelled by finite element method (FEM), and the fuzzy control algorithm for the MRB is then designed. Furthermore, several types of seismic wave is introduced to simulate and the experiments are carried out to investigate the different response along the bridge with the results show that the isolating performance of passive MRB is similar to that of traditional LRB, which ensures the fail-safe capability of MRB. In addition, the controllable MRB embodies the advantage of isolating capacity and energy dissipation, because the displacement of bearing decreased by 34.1%. The shear force from the pier top is also alleviated.

Introduction

Bridge is an important part of the transportation lifeline. There will be great impact force between beam and pier when the bridge is under the threats of earthquakes and overloaded vehicles. It may cause pier-beam structure damage and even collapse. It also would do harm to people's lives and property, further to the economic development [1]. Therefore, reducing the dynamic response and improving the isolating capacity of the pier-beam structure have become a key issue that should be solved in the field of bridge construction.

At present, we have used many kinds of passive bearings for the bridge isolation, and the cycle time of vibration is extended to reduce the damage of beam and pier in earthquake. The scholar Tang [2] came up with the main factors of influencing the laminated rubber bearing sliding reaction; and some other scholar brought up the method that combined the adjustable damper and passive rubber bearing to restrain the support system's vibrational energy. But we also face the difficulties: it is hard to deal with the contradiction of reducing the bridge displacement and reducing the pier transfer force [3, 4] under the condition that passive bearings could not be intelligent regulated due to limitation of the materials and structural parameters. Some scholars [5, 6, 7, 8] made a deep research on different MRE materials, and developed the adjustable stiffness isolation bearing for the building vibrating isolation. The experiment results show that the magneto-rheological bearing (MRB) can change the natural frequency, but there were few reports that the MRE apply to the bearing.

These papers take advantage of the adjustable stiffness and damping of MRE, and use MRB which is made up of MRE to replace the traditional passive bearing. Moreover, on the basis of bridge-bearing finite element model, we compared the isolation disadvantages and advantages of passive bearings, passive MRB system and controlled MRB system along the direction of bridge.
**Bridge Isolation Model of Nonlinear MRB**

**Analysis Model of Three-span Continuous Bridge**

The three-span continuous isolated bridge is regarded as the research object. Substructure of the bridge is composed by rigid reinforced concrete. In the process of seismic excitation, the superstructure of the bridge and piers are linear elastic. The experiment is assumed that the bottom of the pier is fixed (the pier is rigidly fixed at the foundation), regardless of the pier-soil interaction, the abutment is rigid and each pier is arranged with the isolation bearings. At the same time, it is assumed that the bridge deck is straight, the bridge in longitudinal direction is supported by bridge piers, and the bridge piers and bridge deck are orthogonal.

In this paper, we study the dynamic response of the pier-beam structure along the bridge under the seismic load. According to the above assumptions, the bridge structure can be discrete as the finite element model of the quality system that is shown in Fig. 1. The degree of freedom of every node in longitudinal direction is considered. We choose consistent acceleration input model [9] is adopted as the seismic excitation which is introduced from foundation to investigate the seismic response along the bridge.

![Figure 1. Finite element method model of three-span continuous isolated bridge.](image)

**Design and Test of MRB**

Considering the new product production process and laboratory conditions, according to the design criteria of MRB and pier-bearing shear stiffness under the impact loads, based on the dimensionless similarity theory, the MRB is researched and produced independently, and it is processed into small-scale MRB prototype (based on the similar coefficient of the horizontal equivalent stiffness \( S_S \) shown in Eq. (1). The maximum shear displacement of prototype is designed as 30% of MRB.

\[
S_S = \frac{\text{Small-scale MRB stiffness}}{\text{Full-scale MRB stiffness}}
\]  

(1)

MRB independent research and development of small-scale, experimental test, the external mechanical phenomena of the small-scale MRB show stiffness and damping adjustable and hysteresis. It can be represented by the Bouc-Wen hysteretic model proposed by M.Behrooz et al [10] and the phenomenon model with stiffness and viscous damping of MRB. And the MRB shear restoring force \( F_d \) can be expressed as:

\[
F_d = a_m z + k_1 (x - y) + c_1 (\dot{x} - \dot{y}) + k_m x + c_m \dot{x}
\]

(2)

and \( k_y = k_2 (x - y) + c_2 (\dot{x} - \dot{y}) \)

(3)

The hysteretic displacement \( z \) in the Eq. (2) is decided by the Eq. (4).

\[
\dot{z} = -\gamma |z| |\dot{z}|^{\alpha} - \beta |z|^{\beta} + A
\]

(4)

The basic parameters \( A, \beta, n, \gamma \) can be estimated based on the existing value of the bearing [10]. Both The stiffness \( k_m \) and damping parameters \( c_m \) of MRB and hysteresis effect coefficient...
and the excitation current have linear relationship. They are shown in formula (5)-(7).

\[ k_m = k_{m0} + I \]  
\[ c_m = c_{m0} + I \]  
\[ a_m = a_{m0} + I \]  

In the formula (5)-(7), \( k_{m0} \) is the initial stiffness coefficient, \( c_{m0} \) is the initial damping coefficient, and \( a_{m0} \) is the initial hysteresis effect coefficient. With the corresponding, \( k_{m1}, c_{m1}, a_{m1} \) are stiffness, damping, hysteresis coefficient changed with current \( I \).

**Vibration Equation of Bridge and Control Strategy of MRB**

Since the actual bridge-bearing system is relatively complex, finite element approach is adopted to build the isolation model of vibrational bridge. When the seismic excitation is inputted, the seismic response from every node of the whole model can be observed. Meanwhile, the MRB is controlled according to the mechanical behavior of the bridge.

**Establish and Solve the Vibration Equation of Bridge**

With the seismic excitation, the vibration equation of discrete isolation bridge shown in Fig. 2 can be expressed as:

\[ [M]\{u\}_{(t)} + [C]\{\dot{u}\}_{(t)} + [K]\{u\}_{(t)} + D[F_d] = -[M]\{r\}_{(t)} \]  

In the Eq. (8), \([M],[C],[K]\) represent the mass, damping and stiffness matrix of the bridge-bearing system respectively, \([D]\) means the partial matrix of the restoring force of bearing, \([F_d]\) is the storing force of the bearing, \(\{u\}_{(t)}\) is the ground motion acceleration. \([r]\) is the mass inertia force position matrix caused by earthquakes. \(\{u\}_{(t)}, \{\dot{u}\}_{(t)}, \{\ddot{u}\}_{(t)}\) respectively represent the displacement, velocity and acceleration column vector of the bridge structure.

Because the Eq. (8) is a nonlinear equation, this article solves system dynamics equation by Newmark – \(\beta\) method.

**Design of MRB Control Strategy**

It is shown in section 1.2 that while the control current related to the vibration status of the beam-pier structure is applied to the coils of the MRB, the natural frequency can be changed and the structural strength can be improved by adjusting the stiffness. At the same time, the energy dissipation capacity can be improved through adjusting the damping. Because the complexity of bridge structure makes it difficult to build an accurate model, this paper adopts the fuzzy inferences to control the isolation of MRB, and the input variable is the displacement of the bearings and the acceleration response of bridge deck, the output variable is drive current of MRB. The fuzzy controller of MRB is shown in Fig. 2.
In this paper, the EI-Centro, Tianjin seismic waves are selected as the random seismic load input. For example while the excitation is the EI-Centro (N-S) seismic wave, along with the effect of LRB, the peak deck acceleration is 1.071 m/s² and the peak support displacement is 0.083 m. Therefore, the basic domain of the deck acceleration can be set as \([-1.5 \, \text{m/s}^2, 1.5 \, \text{m/s}^2]\), and the basic domain of the support displacement can be set as \([-10 \, \text{cm}, 10 \, \text{cm}]\). The fuzzy controller output variables are determined by the current value \(I\) supplied to the MRB. Its basic domain is set as \([0A, 4A]\). When the output variable is 0, the MRB is not supplied the current (the MRB is working in passive condition).

In order to synthetically consider the relationship of the deck acceleration, bearing shear displacement and the mechanical properties of MRB, the fuzzy control rules are designed to obtain bridge isolation effect in Table 1. Mamdani method is used to inference and the weighted mean method is used to resolute the ambiguity, then the clear value of control system outputs is obtained.

Table 1. Fuzzy control rules.

<table>
<thead>
<tr>
<th>Support displacement</th>
<th>Deck acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>PL, PL, PS, PS</td>
</tr>
<tr>
<td>NS</td>
<td>PL, PM, ZE, PS, PM</td>
</tr>
<tr>
<td>ZE</td>
<td>PM, PS, ZE, PS, PM</td>
</tr>
<tr>
<td>PS</td>
<td>PM, PS, PS, PM, PL</td>
</tr>
<tr>
<td>PB</td>
<td>PS, PS, PS, PL, PL</td>
</tr>
</tbody>
</table>

Simulation Study on Shock Response of Bridge

A three-span continuous simple supported bridge is regarded as the research object, of which the span is 3x20 meters. The model parameters of the full-scale MRB are magnified in equal proportion according to the model parameters of the small-scale MRB in section 1.2.

Simulation Design of Bridge Vibration System

Superstructure of the bridge employs the uniform-section double-column pier that is made of reinforced concrete with single box and triple cells. The pier high six meters. The basic parameters of bridge pier-beam structure are shown in Table 2.

Table 2. Basic parameters of the bridge structure.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sectional area (m²)</th>
<th>Moment inertia (m⁴)</th>
<th>Density (T/m³)</th>
<th>Elasticity modulus (Gpa)</th>
<th>Quality per meter (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>3.04</td>
<td>1.77</td>
<td>2.4</td>
<td>2.8</td>
<td>7.296</td>
</tr>
<tr>
<td>Pier</td>
<td>2.45</td>
<td>0.39</td>
<td>2.4</td>
<td>2.8</td>
<td>5.880</td>
</tr>
</tbody>
</table>

The response of the bridge structure with different excitation is studied by comparing the MRB with the typical LRB. The performance parameters of the LRB are shown in Table 3.

Table 3. Performance parameters of LRB.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Bearing capacity (KN)</th>
<th>Pre-yield stiffness (KN/mm)</th>
<th>Post-yield stiffness (KN/mm)</th>
<th>Yield shear force (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values</td>
<td>491</td>
<td>35.4</td>
<td>3.54</td>
<td>54.87</td>
</tr>
</tbody>
</table>

The Bouc-wen model is adopted to simulate the constitutive relation of the LRB [11]. The shape parameters of optimized LRB are \(A, \beta, \gamma, n\) the corresponding values are 2, 1m⁻², 10m⁻², 1.

The actual construction parameters of the simulation bridge, the performance parameters of LRB and the MRB model parameters from the reference [10] is considered into the determination of the passive MRB bearing parameters. Based on the experimental data of the small-scale MRB, the parameter identification method is used into the determination.
Random seismic waves are input to the model of bridge structure for simulation as simulative impact loads. The peak acceleration of four different random seismic waves [11] is presented in Table 4. These four seismic records are El-Centro wave (N-S direction), El-Centro wave (E-W direction), Tianjin wave (N-S direction) and Tianjin wave (E-W direction).

Table 4. Four kinds of seismic waves and their acceleration peaks.

<table>
<thead>
<tr>
<th>Seismic wave</th>
<th>Component</th>
<th>$a_{max}$ (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>El-Centro N-S</td>
<td></td>
<td>3.417</td>
</tr>
<tr>
<td>El-Centro E-W</td>
<td></td>
<td>2.101</td>
</tr>
<tr>
<td>Tianjin N-S</td>
<td></td>
<td>1.458</td>
</tr>
<tr>
<td>Tianjin E-W</td>
<td></td>
<td>-1.042</td>
</tr>
</tbody>
</table>

Analysis the Response of Bridge Structure with Random Seismic Excitation

In the simulation, a representative El-Centro (N-S direction) seismic wave is selected as the excitation to study the support displacement and the pier top shear of the isolation system under three different kinds of bearings form. The three types of bearings are passive LRB, passive MRB (not control) and controlled MRB. The results of the simulation are shown in Fig. 3. The results of both observations corresponds’ power spectrum are seen in Fig. 4.

Figure 3. Time-history contrast of bridge structure response by El-Centro (N-S) seismic input.

From Fig. 3 can be seen, in the early response of the bridge structure with random seismic excitation, there are no significant differences of displacement peak, the pier top shear between LRB and passive MRB. However, in the late seismic response, the passive MRB reflects better damping ability than the LRB. Compared with the passive LRB system and passive MRB system, the MRB system which is controlled by using a control mode in section 2.2 can reduce the support displacement and the pier top shear obviously.

The above analysis shows that the passive bearings for bridge anti-earthquake have some effect. But due to the defects of its parameter regulation, the passive bearings produce a larger displacement than the controlled MRB to dissipate energy and reduce the damage. Controlled MRB system can adjust their stiffness and damping parameters to balance the support displacement, shear force and energy dissipation capacity. So it has good earthquake mitigation and isolation ability.
The Fig. 4 shows that the response frequency of bridge pier-beam structure with earthquake is within 0.3Hz-2Hz. Compared with the LRB, MRB owns better performance of seismic isolation and energy dissipation with the frequency of seismic excitation, while also ensuring MRB out of control in the course of security.

Conclusions

Under different excitations of multiple seismic waves, there is no difference in passive LRB and passive MRB in the aspects of pier-beam displacement, pier top shear. This shows that under the condition when no control signal is applied, the MRB and traditional passive bearings having common isolating features, which has an excellent fail-safe property. Controlled MRB can reduce the pier-beam displacement by 35% and significantly reduce the pier top shear, which is also responsive. All these show that the controlled MRB can reduce the pier-beam transfer force and displacement by adjusting their stiffness, damping parameters. Also the controlled MRB acts better in vibration isolation compatibility and energy dissipation capacity.

By reasonable modeling to set nonlinear structural parameters and control parameters of the MRB, we can guarantee the fail safe and control performance of MRB, which is feasible for the controlled MRB to replace the passive bearings. This provides a theoretical foundation and technical support for the further structure design, parameter optimization, control improvement and bench test.

Acknowledgements

This work was supported by the National Nature Science Fund of People’s Republic of China (Project NO.11372366), Chongqing Science Fund for Distinguished Young Scholars (cstc2014jcyjjq40004), Chongqing postgraduate research and innovation project (CYS14145) and Chongqing Excellent Talents Plan for Universities and Nature Science Fund of Chongqing (cstc2012jjA40035).

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