Numerical Investigation of Smart Base Isolation System Employing MR Elastomer

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Abstract. This paper evaluates the dynamic performance of a newly proposed smart base isolation system employing Magneto-Rheological Elastomers (MREs). MREs belong to a class of smart materials whose elastic modulus or stiffness can be adjusted by varying the magnitude of the magnetic field. The base isolation systems are considered as one of the most effective devices for vibration reduction of civil engineering structures in the event of earthquakes. The proposed base isolation system strives to enhance the performance of the conventional base-isolation system by using controllable MREs. To validate the effectiveness of the MRE-based isolation system, an extensive simulation study has been performed using a five degree-of-freedom structure under several historical earthquake excitations. The results show that the proposed system outperformed the conventional system in reducing the responses of the structure in all the seismic excitations considered in the study.

1. Introduction

Hybrid-type base-isolation systems have been developed in recent years to improve the performance of passive-type base isolation systems. In the 1980s and early 1990s, considerable attention was paid to an active control device-based hybrid system (e.g., \cite{5,7}). However, active control-based hybrid systems have many problems, like instability, reliability, power consumption, etc. These issues therefore limited their implementation in large-scale structures. Consequently, later researchers focused on the feasibility of semi-active control devices for seismic response reduction of base-isolated structures which can be both adaptable and stable, while maintaining low external power requirements (e.g., \cite{1}). A smart structural control system employing semi-active control devices (i.e., MR fluid dampers) was proposed and studied by \cite{6} and \cite{8}.

Recently, a new type of semi-active base-isolation system has been proposed to incorporate Magneto-Rheological Elastomers (MREs) in base-isolation systems. MREs contain micron-sized magnetisable particles embedded in elastomeric or rubber-like solids (e.g., silicone rubber or natural rubber). The application of a magnetic field to the elastomers increases their spring rate of stiffness \cite{3}. Moreover, MREs may overcome several difficulties that MR fluids have such as deposition, environmental contamination and sealing problems because of their unique feature. For civil engineering applications of MREs, Hwang et al. \cite{4} carried out a conceptual study on the application of MREs to base isolation systems for building structures. However, the feasibility of MREs to base-isolated structures has not been fully explored. As such, this paper intends to investigate the feasibility of the smart base-isolation system employing MREs by conducting numerical simulations. For a
dynamic model of MREs, a semi-active stiffness device model proposed by Gandhi et al. [2] is used. In numerical simulations, the six degree-of-freedom structural model coupled with the base-isolation system is considered [6], and three scaled historical earthquakes (El Centro, Northridge, and Hachinohe) are used as input ground motions.

2. Smart Base Isolation System based on MR Elastomers

2.1. System Model

A simple representation of the system is shown in Figure 1. When the isolation layer is added to the structural model, the whole structural model can be treated as a 6-DOF system. In Figure 1, \( M_b \), \( K_b \), and \( C_b \) represent the mass of the isolation layer, the stiffness and the damping coefficient of the base isolator, respectively. The variable stiffness of the MREs is represented as \( K(t) \). The system parameters are: \( M_b = 6800 \text{ kg} \), \( M_1 = M_2 = M_3 = M_4 = M_5 = 5897 \text{ kg} \), \( K_1 = 232 \text{ kN/m} \), \( K_2 = 33732 \text{ kN/m} \), \( K_3 = 29093 \text{ kN/m} \), \( K_4 = 28621 \text{ kN/m} \), \( K_5 = 24954 \text{ kN/m} \), \( K_6 = 19059 \text{ kN/m} \), \( C_b = 3.74 \text{ kN·s/m} \), \( C_1 = 67 \text{ kN·s/m} \), \( C_2 = 58 \text{ kN·s/m} \), \( C_3 = 57 \text{ kN·s/m} \), \( C_4 = 50 \text{ kN·s/m} \), \( C_5 = 38 \text{ kN·s/m} \).

2.2. MRE System Modelling

To describe the dynamic behaviour of MREs, they are considered as a semi-active controllable stiffness device. In other words, their total stiffness, which can vary according to the external input current (magnetic field), is denoted as \( K(t) \). The system parameters are: \( M_b = 6800 \text{ kg}, M_1=M_2=M_3=M_4=M_5=5897 \text{ kg}, K_1 = 232 \text{ kN/m}, K_2 = 33732 \text{ kN/m}, K_3 = 29093 \text{ kN/m}, K_4 = 28621 \text{ kN/m}, K_5 = 24954 \text{ kN/m}, K_6 = 19059 \text{ kN/m}, C_b = 3.74 \text{ kN·s/m}, C_1 = 67 \text{ kN·s/m}, C_2 = 58 \text{ kN·s/m}, C_3 = 57 \text{ kN·s/m}, C_4 = 50 \text{ kN·s/m}, C_5 = 38 \text{ kN·s/m} \).

2.3. Equations of Motion

Neglecting the nonlinear effects and denoting the base and storey displacements relative to the ground by \( x = [u \ x_1 \ x_2 \ x_3 \ x_4]^T \), the equations of motion of the base-isolated system may be expressed as

\[
M \ddot{x} + C \dot{x} + K(t) = -M \ddot{g}
\]
or

\[ M \ddot{x} + C \dot{x} + K_0 x = \Lambda f - M \Gamma \dddot{x}_g \] (5)

where \( M, C \) and \( K \) are the mass, damping, and stiffness matrices are, respectively, \( f \) is the supplemental force exerted by the MREs, \( \Lambda = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix} \) the position of the supplemental damper force, \( \Gamma \) vector whose elements are all unity, \( \dddot{x}_g \) the ground acceleration. Defining the state vector \( z = \begin{bmatrix} x & \dot{x} & \ddot{x} \end{bmatrix}^T \), the output vector to be regulated \( y = \begin{bmatrix} x & \dot{x} & \dddot{x} \end{bmatrix}^T \), the state-space form of the equations of motion is given by

\[ \dot{z} = Az + Bf + E \dddot{x}_g \] (6)

\[ y = Cz + D_y f + F_y \dddot{x}_g \] (7)

3. Numerical Simulation Results

To verify the feasibility of the MRE-based smart base isolation system, numerical simulations are carried out using the simulation model above along with the system parameters provided in section 2. The LGR control was implemented to regulate the stiffness of the MRE. The numerical simulation results of hybrid system employing MREs are compared to those of a passive-type base isolation system using rubber bearings (RB).

Figure 2 shows the storey drifts at the first floor for each system for various earthquake inputs. As shown in the figure, the smart base isolation system employing MREs significantly reduce the response compared with the passive-type base isolation system for various excitations. Figures 3 and 4 compare the peak storey drift at the first floor and the peak acceleration at the top floor for each earthquake input, respectively. The results show that the MRE base-isolation outperforms the conventional base-isolation system.

**Figure 2.** Storey drift at first floor for various earthquake inputs

**Figure 3.** Storey drift at first floor for various earthquakes

**Figure 4.** Structural acceleration at top floor for various earthquakes
Table 1 shows the percent response improvement of the base isolation system using MREs as compared with the passive base-isolation system under different earthquake inputs. These results demonstrate that the MRE-based smart base-isolation system can significantly reduce the structural accelerations and storey drifts as well as the base displacements (or isolator deformations).

**Table 1. Percent response improvement compared to the conventional base isolation system**

| Earthquake  | Base displacement | Storey drift at first floor | Structural acc. at top floor |
|-------------|-------------------|-----------------------------|-----------------------------|
| El Centro   | 20.6 %            | 17.4 %                      | 25.7 %                      |
| Northridge  | 38.5 %            | 27.3 %                      | 10.3 %                      |
| Hachinohe   | 45.3 %            | 43.7 %                      | 39.0 %                      |

4. Conclusions
This paper investigated the feasibility of the MRE base-isolation system by evaluating the dynamic performance of the system. In this study, MREs are idealized as a controllable stiffness device. To study the control performance of the MRE-based smart system, numerical simulations were conducted by using a 5-DOF structure model. The performance of the MRE-based system is compared to that of the passive base isolation system, which uses rubber bearings. The numerical simulation results show that all the responses (base drift, structural acceleration and inter-story drift) of the MRE base-isolation system were smaller than those of the passive system, indicating that the MRE system outperformed its passive counterpart. In summary, this simulation study validated the feasibility of the MRE base-isolation system as a new “smart” base-isolation system, and more studies (including experiments) should follow to further validate the effectiveness of the MRE system.

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