Reducing damages against earthquakes has been an important issue for decades. This study proposes a three-dimensional seismic isolator, which also can reduce the vibrations caused by not only earthquakes but also force acting on the object on the isolator. Then this system can be called the vibration controller/isolator. The MR (magneto rheological fluid) damper was used to change the damping coefficient according to the control algorithm. When the base shakes and isolation is needed the damping coefficient must be small and when the force acts and damping force is needed the damping coefficient must be large. Then the damping coefficient of MR damper was controlled according to displacements and velocities of the base and the object. The isolator must keep horizontal otherwise the object on the isolator easily falls down. Therefore, the system had a tilt prevention mechanism by means of parallelogram linkages. Two units of linkages, each of which consists of two parallelograms, were used for the three-dimensional motion. The performance of the proposed isolator was investigated by both simulation and experiment. Since the MR damper had not only rheological damping force but also friction force, the friction force was considered in the theoretical analysis. The results showed that the vibration caused by force was reduced very well and the vibration caused by the motion of base was also reduced well. Since the structure is very simple and effective, this system can be applied not only to seismic isolator but also to IC tip production systems and to precision measuring devices.

1. Introduction

Seismic isolators are often used as a means of preventing objects from shaking or toppling by earthquakes. Most isolators hold the object flexibly to improve the isolation function. In contrast, to
defend objects from the vibration caused by external force, stiff support would be required. Therefore, there are tradeoffs between the two functions, isolating and vibration suppressing and it is not able to satisfy both of them by passive control.

One of the methods to solve that problem is to lock the system with a rigid component and when a big earthquake occurs, make the rigid part broken by the energy of the quake to put the isolator into operation. That does make the object avoid from vibration by force, however, if the size of the earthquake is not big enough the object would receive the oscillation of the quake directly.

In this research both functions were achieved by controlling a MR (magneto rheological) damper semi-actively[1]. The MR damper is possible to change the damping coefficient according to the current of electricity[2]. The proposed isolator has a tilt prevention mechanism consisted of parallelogram linkages. The performance of the isolator will be investigated by both simulation and experiment.

2. Proposed Vibration Controller/Isolator

Figure 1 depicts the elevation view of the three-dimensional vibration controller/isolator proposed in this study. A three-dimensional vibration controller/isolator needs to enable the isolator table to move in the vertical direction as well as in the horizontal direction. To make that possible, two sets of parallelogram linkage units are installed perpendicularly as shown in Figure 1. By using two parallelograms for each unit, the horizontal and vertical movements become virtually independent with each other. In addition, hinges that connect linkages units with a base stage and the isolation table enable the table to move in any directions without constraint. The tables are supported by coiled springs. Figure 2 shows the movement of the linkages moving horizontal and vertical in the frontal view. The isolator table is, of course, able to move in any direction in the horizontal plane.

3. MR (magneto rheological) damper

3.1 Features of the MR damper

Figure 3 shows a cross-section view of the MR damper RD 1097 produced by the Lord Corporation. A layer of polyurethane foam saturated with MR fluid surrounds a steel core and coil. These elements form a piston on the end of a shaft that is free to move axially inside a steel tube.
Application of magnetic field causes the MR fluid to develop magnetic chains and resist shear direction. The response of the MR damper against the field is fast and high-power so the damping can be changed easily by adjusting the electric current in the coil.

The damping of the MR damper includes not only viscous drag but also friction drag. To make the system linear, the equivalent viscous damping term of the friction drag is possible to calculate, by investigating the dissipated energy of the damper in one cycle. However, the dissipated energy by the friction drag depends on the magnitude of displacement of the damper, and in case of earthquakes, displacements change irregularly so the analyses in this study will use values of the viscous and friction drags directly.

3.2 Control Algorithm

To control the MR damper semi-actively, a control algorithm would be needed. There is a law proposed by Kransnicki\[3\], which is written below,

\[
C = \begin{cases} 
C_H, & \text{if } \dot{x}(\dot{x} - \dot{x}_0) \geq 0 \\
C_L, & \text{if } \dot{x}(\dot{x} - \dot{x}_0) < 0 
\end{cases}
\]

(1)

where \(C\) is the viscous damping coefficient of the damper, \(C_H\) is a higher value, \(C_L\) is a lower value, \(x\) is the displacement of the isolator table and \(x_0\) is the displacement of the base. This law was proposed for isolation, but can be used for vibration suppressing also. This is because if there is no displacement at the base, the damping should be large, to make it stiffer to resist against external force. In this case, it becomes \(\dot{x}_0 = 0\), so the expression \(\dot{x}(\dot{x} - \dot{x}_0) = \dot{x}^2\) will be over 0 at all times, and the damping becomes \(C_H\). As mentioned before, the damping of the MR damper includes both viscous and friction drags, and both of them increase in proportion to the value of electricity, so the law will be slightly modified as below,

\[
I = \begin{cases} 
I_H, & \text{if } \dot{x}(\dot{x} - \dot{x}_0) \geq 0 \\
I_L = 0, & \text{if } \dot{x}(\dot{x} - \dot{x}_0) < 0 
\end{cases}
\]

(2)

where \(I\) is the current value of electricity, \(I_H\) is a higher value and \(I_L\) is a lower value of that.

3.3 Influence of friction

Here, two models will be compared; one without friction, another with friction. This comparison will be useful to investigate the influence of friction on seismic isolation and vibration suppressing. The dynamic model used here is shown in Figure 4. The mass is connected to the base via spring, dashpot and friction elements.

![Figure 3 Cross Section of MR damper (RD 1097).](image)

**Figure 3** Cross Section of MR damper (RD 1097).

![Figure 4 One degree of freedom spring-mass- damper-friction system.](image)

**Figure 4** One degree of freedom spring-mass- damper-friction system.
In this system, \( M \) represents the mass of the object, \( K \) is the stiffness coefficient of the spring, \( C \) is the viscous damping coefficient, \( F_{in} \) is the external force and \( F_j \) is friction force. The damping coefficients \( C_H \) (when \( I = I_H \) ), \( C_L \) (when \( I = I_L = 0 \) ) were set to make each of the damping ratio \( \zeta_H \), \( \zeta_L \) become 0.75 and 0.25, respectively. The values of each parameter are listed in Table 1.

<table>
<thead>
<tr>
<th>( M )</th>
<th>1.0 kg</th>
<th>( K )</th>
<th>50 N/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \zeta_H )</td>
<td>0.75</td>
<td>( \zeta_L )</td>
<td>0.25</td>
</tr>
<tr>
<td>( C_H )</td>
<td>10.6 Ns/m</td>
<td>( C_L )</td>
<td>3.5 Ns/m</td>
</tr>
<tr>
<td>( A )</td>
<td>10 mm</td>
<td>( B )</td>
<td>1.0 N</td>
</tr>
</tbody>
</table>

### 3.3.1 Case with no friction

If there is no friction \( (F_j = 0) \) in the system, the equation of motion becomes as below,

\[
M\ddot{x} + C(\dot{x} - \dot{x}_0) + K(x - x_0) = F_{in}.
\]

Figure 5 (a) shows a set of transfer functions \( |X/X_0| \) when external force is zero and the base motion is sinusoidal \( (x_0 = X_0 \sin \omega t) \). One line is \( |X/X_0| \) when controlled passively by \( C = C_H \), another is when controlled passively by \( C = C_L \), and one more when controlled semi-actively between the two values \( C = C_L \) and \( C = C_H \). Figure 5 (b) shows a set of non-dimensional compliance \( |X/X_a| \) when base motion is zero and sinusoidal external force \( (f_0 = F_0 \sin \omega t) \) is applied. In this case, as mentioned in section 3.2, the response of passive control with high damping and semi-active control becomes the same, so only two frequency responses are depicted. The natural frequency \( f_0 \) of the system is 1.1 Hz, and \( x_a = |F_0|/K \) is the static displacement of the system.

\[
\frac{|X|}{|X_0|} = \begin{cases} 
\frac{A}{1 + \zeta^2 f^2}, & \text{if } \zeta > 1 \\
\frac{A}{1 + \zeta f}, & \text{if } \zeta < 1 \\
A, & \text{if } \zeta = 1
\end{cases}
\]

![Figure 5](image)

### 3.3.2 Case with friction

If there is friction in the system, a stick-slip phenomenon can be seen. In this subsubsection, the friction will be introduced into the simulation. If no external force and only base displacement excitation is applied, the equation of motion and the friction force \( F_i \) is defined as,

\[
M\ddot{x} = -F_i - K(x - x_0) - C(\dot{x} - \dot{x}_0),
\]

\[
F_i = \begin{cases} 
\text{sgn}(\dot{x} - \dot{x}_0)F_{st}, & \text{if } \dot{x} - \dot{x}_0 \neq 0 \\
F_{sum}^{F_{st}}, & \text{if } |F_{sum}| \leq F_{st}, \dot{x} - \dot{x}_0 = 0 \\
\text{sgn}(F_{sum})F_{st}, & \text{if } |F_{sum}| > F_{st}, \dot{x} - \dot{x}_0 = 0
\end{cases}
\]
\[ F_{\text{sum}} = -M \ddot{x}_0 - K (x - x_0) - C (\dot{x} - \dot{x}_0) , \]  
\[ (6) \]

where \( F_{\text{st}} \) is maximum static friction force and \( F_{\text{sl}} \) is dynamic friction force. Likewise, if only external force is applied, the equation of motion and friction force \( F_t \) will be defined as,

\[ M \ddot{x} = F_{\text{in}} - F_t - K x - C \dot{x} \]  
\[ (7) \]

\[ F_t = \begin{cases} 
\text{sgn}(\dot{x}) F_{\text{sl}}, & \text{if } \dot{x} \neq 0 \\
0, & \text{if } \left| F_{\text{sum}} \right| = F_{\text{sl}}, \dot{x} = 0 \\
\text{sgn}(F_{\text{sum}}) F_{\text{sl}}, & \text{if } \left| F_{\text{sum}} \right| > F_{\text{sl}}, \dot{x} = 0 
\end{cases} \]  
\[ (8) \]

\[ F_{\text{sum}} = F_{\text{in}} - K x - C \dot{x} \]  
\[ (9) \]

Figure 6 shows the responses to sinusoidal base excitation \( x_0 = 0.01 \sin 2 \pi t \) (m) and Figure 7 shows the responses to sinusoidal external force \( F_{\text{in}} = 1.0 \sin 2 \pi t \) (N) while changing the values of friction force. The materials parameters are listed in Table 2, the different values of friction when \( F_{\text{in}} = 0 \) are listed in Table 3 and the values of friction when \( x_0 = 0 \) are in Table 4.

**Figure 6** Time Response under three different friction force when \( x_0 = 0.01 \sin 2 \pi t \) (m) and \( F_{\text{in}} = 0 \) (N).

**Figure 7** Time Response under three different friction force when \( x_0 = 0 \) (m) and \( F_{\text{in}} = 1.0 \sin 2 \pi t \) (N).
Table 2 Parameters of the system.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>M</strong></td>
<td>1.0 kg</td>
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<tr>
<td><strong>C</strong></td>
<td>10 Ns/m</td>
</tr>
<tr>
<td><strong>K</strong></td>
<td>50 N/m</td>
</tr>
<tr>
<td><strong>f</strong></td>
<td>1.0 Hz</td>
</tr>
</tbody>
</table>

Since stick-slip occurs because of friction, the stick-slip must be implemented in calculation. The two figures in Figure 8 show the displacement transmissibilities and non-dimensional compliances in case friction is introduced into simulation.

![Figure 8](image)

**Figure 8** Simulated frequency responses with friction.

4. **Experiment of the proposed Vibration Controller/Isolator**

4.1 **Experimental apparatus**

Figure 9 shows the dynamic model and picture of the proposed table. Damper 1 and Damper 2 represent the MR dampers set for the horizontal and vertical direction, respectively. $m$ and $m_i$ are the masses of the object and the upper table, $k_x$ and $k_z$ are the stiffness in $x$, $z$ direction respectively, and $c_x$ and $c_z$ are the coefficient of viscosity of the table in each direction, respectively. $x$ and $z$ are the horizontal and vertical displacements of the table, respectively, and $x_0$ and $z_0$ are the horizontal and vertical displacements of the base, respectively. In addition, $c_{d1}$ and $c_{d2}$ are the coefficient of viscosity of Damper 1 and Damper 2, respectively, and $D_{d1} (\geq 0), D_{d2} (\geq 0)$ are the friction force of Damper 1, Damper 2, respectively. For base excitation, a vibration exciter was used, and for external force excitation, the centrifugal force caused by an eccentric mass on a stepping motor was used.

![Figure 9](image)

**Figure 9** Dynamic model and picture of the proposed table.
4.2 Frequency Response

The parameters of the experimental apparatus are shown in Table 3. \( f_{nx} \) and \( f_{nz} \) are the natural frequencies of the table in \( x \) and \( z \) direction, respectively. The relative displacements of the dampers can be calculated by geometry of linkages. By comparing three results, passive control with \( I = I_L = 0 \), passive control with \( I = I_H \) and semi-actively control according to the control law Eq. (2), the seismic isolation function and the vibration suppression function of semi-active control will be verified. It has to be noted here that systems including coulomb friction become non-linear, so the response varies according to the amplitude of the excitation of base or external force.

Figure 10 shows the displacement transmissibility of \( z \) direction in calculation and experiment. Figure 11 shows the non-dimensional compliance of \( z \) direction derived from calculation and experiment. \( z_{st} \) is the static displacement of this system in \( z \) direction. It has to be specified that the amplitude of base excitation or external force is limited by the stroke of MR damper. From the results of isolation, it is possible to know that, semi-active control works as well as passive control at \( I = I_H \) and much better than passive control at \( I = I_L \) in the frequency range around the natural frequency, and in frequency range much higher than that, it becomes inferior compared to passive control in low electrical current, but better than high electrical current passive control. In vibration suppression, the increase of friction in the MR damper is good to suppress the vibration caused by external force. The reason why the compliance is nearly zero in all frequency range in the red line of Figure 11, is that the static friction in the MR damper is big enough to halt the movement of the linkages. The results also show that the tendency in calculation and experiment is very close.

The results of Figure 10 and Figure 11 are in case the base excitation or external force is limited, as mentioned above. If the stroke of the MR damper were much longer and no limitation was needed for the input excitation or force, results of displacement transmissibility and non-dimensional compliance would become as shown in Figure 12 and Figure 13. The amplitude of \( x_0 \) in Figure 12(a) is 15 cm, \( z_0 \) in Figure 12(b) is 4 cm and amplitude of force in Figure 13 is 15 N.

![Figure 10](image_url)  
**Figure 10** Displacement transmissibility under three control conditions (\( z \) direction).
Figure 11  Non-dimensional compliance under three control conditions (z direction).

Figure 12  Displacement transmissibility in case base input is not limited (|x₀| = 0.15m, |z₀| = 0.04 m ).

Figure 13  Non-dimensional compliance in case force input is not limited (|Fₓ| = |Fₚ| = 15 N ).

5. Conclusion

Three dimensional seismic isolator with MR damper was proposed. MR dampers change their viscous and frictional damping forces according to the current of electricity. A control algorithm was introduced to the MR damper and by that the isolator achieved not only seismic isolating function but also vibration suppressing function. Friction in the MR damper was proved to be effective for vibration suppression. The performance of the vibration controller/isolator was verified by both calculation and experiment.

REFERENCES

