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Hybrid isolation system using friction-controllable sliding bearings
Part 1: Outline of the system

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ABSTRACT: In order to improve the isolation capability of a sliding base isolation system, a hybrid isolation system using a friction controllable sliding bearing has been proposed. By controlling the friction force, the sliding displacement will be confined within an acceptable range, while keeping the overall isolation performance optimal. This paper describes the principle of the friction controllable sliding bearing, and outlines the concept of the hybrid isolation system. Applications of this hybrid isolation to a four story building and a bridge have been considered. Computer simulation has been conducted and the results have demonstrated the improved isolation capability of the proposed system.

1. HYBRID ISOLATION SYSTEM

1.1 System Concept

The hybrid isolation system using friction controllable bearings(VFB) is conceptually depicted in Fig.1 and 2, respectively with a building and a bridge structure resting on the bearings. Each bearing has a fluid chamber which is connected to a pressure control system composed of servo valve, an accumulator and a computer. The friction on the interface between the bearing and its supporting base is controlled by adjusting the fluid pressure in the chamber. The computer calculates an appropriate signal to control the fluid pressure based on the observed structural response acceleration and sliding displacement, and sends it to the pressure control device as shown in Fig.1 and 2.

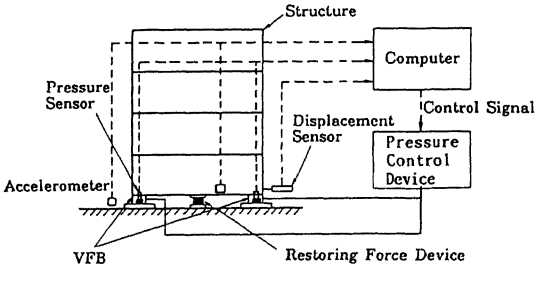

Figure 1. Concept of Hybrid Sliding Isolation System for Buildings

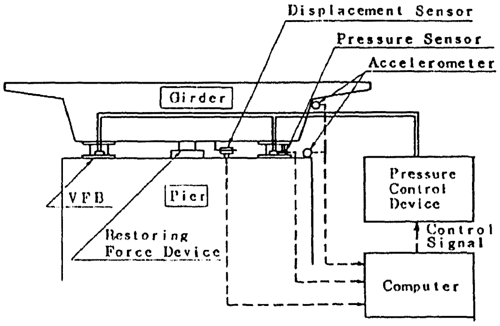

Figure 2. Concept of Hybrid Sliding Isolation System for Bridges

1.2 Friction Controllable Sliding Bearing

The idealized section view of the friction controllable sliding bearing is given in Fig.3. The bearing is a steel disk with a fluid chamber inside which is sealed by a rubber O-ring along the circular perimeter just inside the sliding interface. A sliding material such as PTFE plate is placed on the sliding interface.

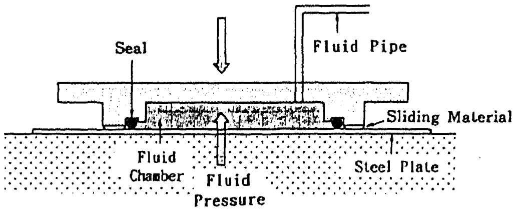

Figure 3. Friction Controllable Bearing (VFB)

1.3 Control Algorithms

Two types of control algorithms for a rigid structure supported by VFB's have been developed. They are based on the instantaneous optimal control theory (Yang, 1988) and bang-bang control concept.

For one degree of freedom model as described in Fig.4, equations of motion are derived as follows.

(1) No sliding ········Phase Ⅰ

$$\dot{x} = 0,\quad x = \mathrm{CONST.} \tag{1}$$

(2) Sliding ···········Phase Ⅱ

$$\ddot{x} = \ddot{z} - f\ \mathrm{sgn}(\dot{x}) \tag{2}$$

$$f = \mu_d\, g$$

(3) Changing Condition (Phase Ⅰ → Phase Ⅱ)

$$|\ddot{z}| > \mu_s\, g \tag{3}$$

(4) Changing Condition (Phase Ⅱ → Phase Ⅰ)

$$\dot{x} = 0 \tag{4}$$

$$|\ddot{x} + \ddot{z}| \leq \mu_s\, g \tag{5}$$

where,

x : relative displacement of mass to ground
$\ddot{z}$: input earthquake acceleration
g : gravity acceleration
μ_s : static frictional coefficient
μ_d : dynamic frictional coefficient

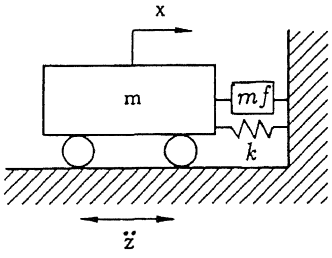

Figure 4. Analytical Model

1. Bang-bang Control : Bang-bang control approach provides a simple and yet effective algorithm. The particular algorithm used in this study facilitates the following control: when the sliding displacement and the velocity of the mass are in the same direction, the pressure control signal u will be decreased to a minimum value u_{min} to increase the friction force in order to put the brake on the sliding. On the other hand, when the sliding displacement and the velocity are in the opposite direction, the pressure control signal will be increased to a maximum value u_{max} to decrease the friction force in order to make the sliding easier as much as possible;

$$u = \begin{array}{l} u_{min}\ ,\ \text{if}\ \mathrm{sgn}(x) = \mathrm{sgn}(\dot{x}) \\ u_{max}\ ,\ \text{if}\ \mathrm{sgn}(x) = -\mathrm{sgn}(\dot{x}) \end{array} \tag{6}$$

2. Instantaneous optimal control : Optimal pressure control signal is determined by minimizing the following time dependent performance index J(t) at every time instant t for the entire duration of an earthquake.

$$J(t) = \alpha x^2 + \beta f^2 + \gamma u^2 \tag{7}$$

where α, β, γ : constants
u : pressure control signal,

The control signal is given in the following equations, where the time delay of the pressure control system is ignored.

$$u = C_0 + C_1 \cdot f + C_2 x \cdot \mathrm{sgn}(\dot{x}) \tag{8}$$

where C_0, C_1 and C_2 are feedback gains. In the actual implementation of this control, however, the control signal u is bounded by the maximum and minimum values, which the hardware can physically supply.

2. APPLICATION TO A BUILDING

A four story reinforced concrete building, in which a passive isolation system using sliding bearing is currently installed, is considered for this study.

Figure 5 illustrates the structural model of this building, and Table 1 shows the values of structural parameters. The damping ratio of h=3 % for the first vibration mode is assumed for the structure. In this study, in order to examine only the effect of the friction, the restoring force device is not considered for the simulation.

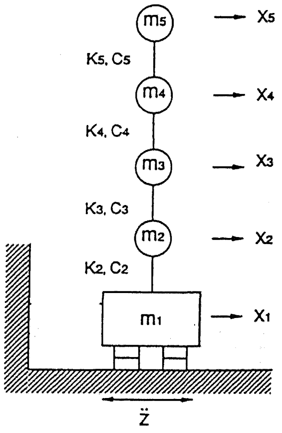

Figure 5. Building Model

Table 1. Structural Parameters

Mass	t	Stiffness	tf/cm
m_1	$5.41 * 10^2$		
m_2	$4.62 * 10^2$	k_2	3007
m_3	$6.29 * 10^2$	k_3	4134
m_4	$5.09 * 10^2$	k_4	5032
m_5	$4.44 * 10^2$	k_5	4897

The performance of the hybrid sliding isolation system is compared with that of the passive system. Figures 6 and 7 show the maximum response acceleration and maximum sliding displacement of the first floor under different intensities of earthquake motion obtained by linearly scaling El Centro record. The hybrid isolation results shown in these figures are under feedback gains of C_0 = 0.0, C_1 = 0.5 kgf s^2/cm^3 and C_2 = -0.1 kgf/cm^3 in Eq. 8, and the coefficient of friction is between 11 and 2 %. The passive isolation results in these figures are under the constant coefficient of friction of 11%, 6%, and 2%.

In the passive isolation system, if small frictional coefficient is used, response acceleration can be small, but the maximum sliding displacement becomes excessive as the input earthquake motion becomes intense. On the other hand, if large frictional coefficient is used, the sliding displacement can be confined within a relatively small range, but the response acceleration becomes very large.

The hybrid control of the friction can solve such problems associated with passive isolation system; the response acceleration can be significantly reduced, while excessive sliding displacement under severe earthquake motion can be prevented. Another advantage of the hybrid system which is observed in the simulation, is that the residual sliding displacement can be maintained almost zero.

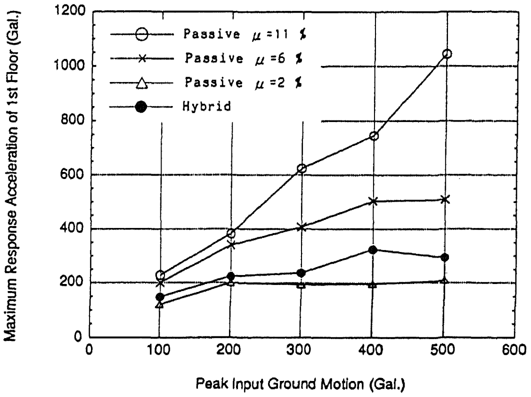

Figure 6. Maximum Response Acceleration

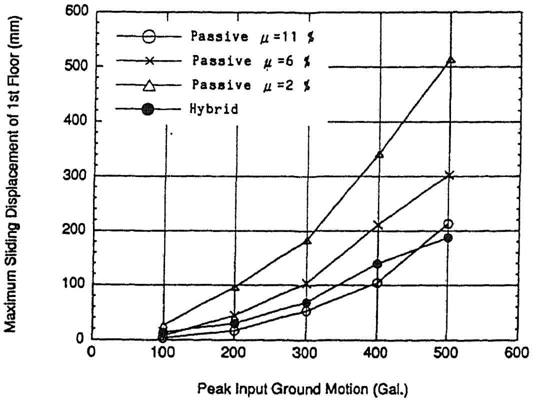

Figure 7. Maximum Sliding Displacement

3. APPLICATION TO A BRIDGE

A simple lumped mass model as described in Figure 4 is considered. The mass(girder) is 501.5 ton and the spring constant of the restoring force device is 0.54 tf/cm. A passive isolation and a hybrid isolation are compared. The coefficient of friction of the passive case is 0.10, while in the hybrid case, it is between 0.03 and 0.20 according to the algorithm described by Eq.8. The standard design earthquake motions for bridge at Level 1(102 Gal) and Level 2(360 Gal) are used as the input motion.

Figure 8 shows the simulation results for the Level 1 earthquake. The passive isolation does not work at this level and the response acceleraion is equal to the input level, 102 Gal. In the hybrid isolation, on the other hand, the coefficient of friction is mostly maintained at the lowest value of 0.03, resulting in the maximum acceleration of about 40 Gal, The maximum sliding displacement is 6 cm, which is considered to be acceptable for Level 1 earthquake.

Figure 9 shows the simulation results for the Level 2 earthquake. It is noted that the coefficient of friction in the hybrid isolation increases where displacement tended to increase, resulting in smaller sliding displacement and a little larger acceleration compared with the passive isolation. The smaller residual displacement observed in this simulation also demonstrated the advantage of the hybrid isolation system.

By adopting the hybrid isolation system, the response acceleration can be reduced at the Level 1 earthquake, while reducing the maximum sliding displacement at the Level 2 earthquake. This result shows the possibility that the hybrid isolation system can offer a better isolation capability for bridges than conventional passive isolation system.

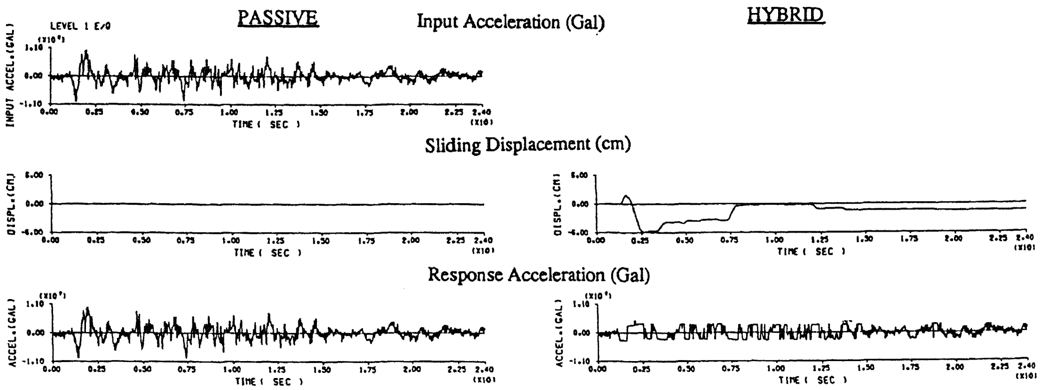

Figure 8. Response to Level 1 Design Earthquake

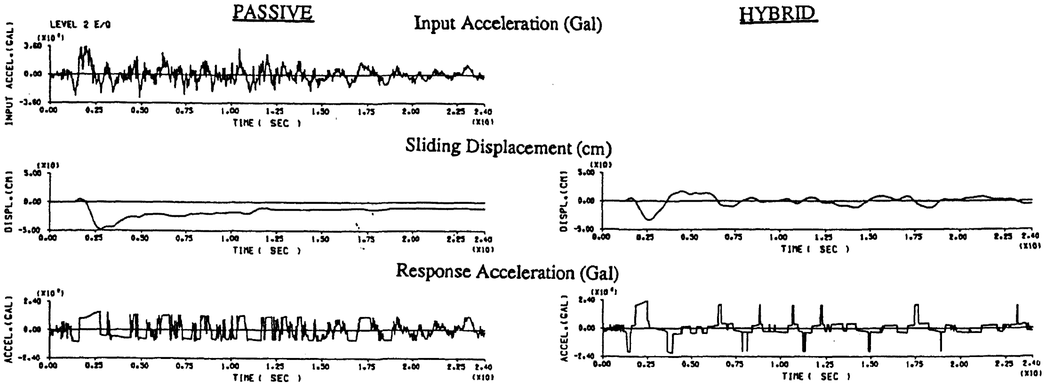

Figure 9. Response to Level 2 Design Earthquake

4. CONCLUDING REMARKS

A hybrid isolation system using friction controllable sliding bearings has been proposed for controlling response of a structure subjected to earthquake motions ranging from low to high intensities. Control algorithm, instantaneous optimal control and bang-bang control, have been developed for controlling the friction force.

Significant advantage of the proposed hybrid sliding isolation system when it is applied to a building or a bridge, has been demonstrated through simulation: (1) for the weak to medium earthquake motions, the coefficient of friction is kept at the minimum value to reduce the seismic force on the structure to a minimum; (2) for strong earthquake motions, the friction is controlled to confine the sliding displacement of the structure to an acceptable range.

REFERENCES

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