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Hybrid isolation system using friction-controllable sliding bearings
Part 2: Shaking table test

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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. A shaking table test and computer simulation have been conducted to clarify the behavior and to demonstrate the efficiency of this system. The friction controllable sliding bearing, pressure control system, and control software have been developed. A model hybrid system has been constructed and tested on a shaking table. From the test results and computer simulation, the response characteristics and controllabilty have been investigated, and the advantage of this system over the passive system has been demonstrated.

1. SHAKING TABLE TEST

A pilot hybrid isolation system has been assembled and tested under one directional horizontal motion on a shaking table. The 3D shaking table of Taisei Technology Research Center at Yokohama, Japan, was used.

1.1 Model Structure

The model structure shown in Fig.1 is a rigid body consisting of a steel frame and steel weights. The total weight of the structure is 12 tf. The model is supported by four friction controllable sliding bearings(VFBs).

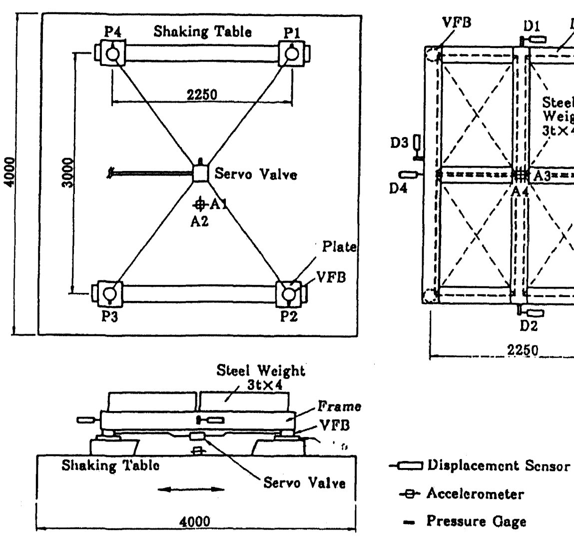

Figure 1. Test Structure

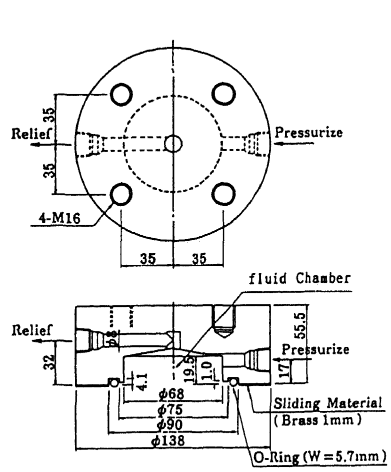

Figure 2. Friction Controllable Bearing (VFB)

The model VFB is shown in Fig.2. The sliding material is a brass sheet of 1 mm thickness and the seal is an O-ring of 5.7 mm in diameter. The area of the sliding interface is 86.0 cm², and the area of the fluid chamber is 57.7 cm² measured to the center of the O-ring width. The supporting plate is a stainless steel sheet attached to a steel plate. A servo valve is located at the center of the model structure from which the fluid is distributed to each VFBs as shown in Fig.1. Accelerations on the shaking table and on the model structure in two horizontal direction, relative displacements between the table and the model structure, and the fluid pressure at each VFBs and at the servo valve, were measured.

1.2 Control System

The control system is shown in Fig.3. The controller is a 16 bit microcomputer (80286) with a numerical coprocessor(80287) to enable faster computation. The response signals measured by the sensors are sent to the microcomputer through 12 bit A/D converter. Then the control signal is calculated according to a certain feedback control algorithm, and applied to the servo amplifier through a 12 bit D/A converter. The interval of measurement is 0.002sec and the interval of control is 0.004sec.

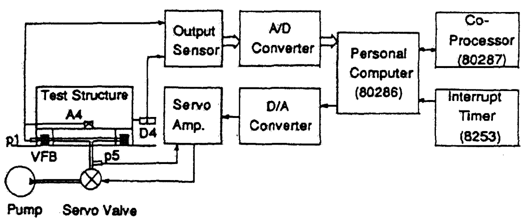

Figure 3. Control System

1.3 Control Algorithms

The following three types of pressure control signals u were applied.

- Passive : u = constant (at 10,20,30,40 and 45kgf/cm²)
- Bang-bang Control :

$$u=\begin{cases} u_{min} = 10\text{kgf/cm}^2, & \text{if } \operatorname{sgn}(x)=\operatorname{sgn}(\dot{x}) \\ u_{max} = 45\text{kgf/cm}^2, & \text{if } \operatorname{sgn}(x)=-\operatorname{sgn}(\dot{x}) \end{cases} \quad (1)$$

- Instantaneous Optimal Control :

$$u=\begin{cases} u_{min} \leqq 51\text{kgf/cm}^2 - C_2|x| \leqq u_{max}, & \text{if } \operatorname{sgn}(x)=\operatorname{sgn}(\dot{x}) \\ u_{max}, & \text{if } \operatorname{sgn}(x)=-\operatorname{sgn}(\dot{x}) \end{cases} \quad (2)$$

where C_2 is a feed back gain.

2. TEST RESULTS

In the Passive cases where the pressure is constant, the response acceleration of the test structure is margined at a certain value α_p which is proportional to the friction coefficient μ_p.

$$\alpha_p = \mu_p \cdot g \quad (3)$$

where g : gravity acceleration

From the measurement of the response acceleration α_p at various levels of pressure p , the relation between the pressure and the friction coefficient μ_p is obtained as illustrated in Fig.4. The friction coefficient shows linear decrease as the increase of pressure, which is approximated by the following equation.

$$\mu_p = 0.125 - 0.00240p \quad (4)$$

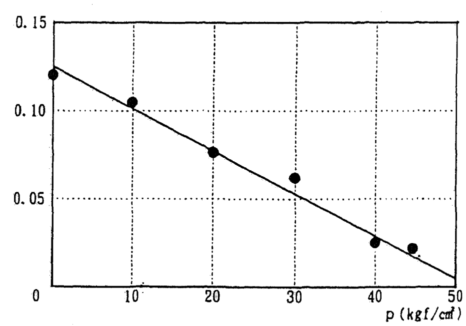

Figure 4. Pressure and Friction

A first order time delay model is assumed between the control signal and the pressure response as described in Eq.5. The time constant T in the equation has been identified by minimizing the sum of square errors between the pressure response from the experiment and that from the model. The identified values of T are 0.029sec for pressure increase and 0.035sec for pressure decrease.

$$T\dot{p} + p = u \quad (5)$$

The modeled relation between the control signal and the pressure response shows good agreement with the test result as shown in Fig.5.

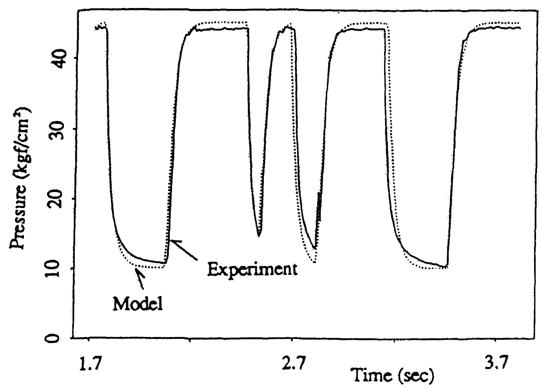

Figure 5. Pressure Time History

The decrease of friction coefficient μ with the increase of sliding velocity was observed in the test. The dependence of the friction coefficient is modeled by the following equation, and the constant k^2 is identified to be 0.11cm/sec from the test result.

$$\mu = \mu_p \cdot \frac{k^2}{\dot{x}^2 + k^2} \qquad (6)$$

The response acceleration $\ddot{x}_m$ computed from the equation (6) by,

$$\ddot{x}_m = \mu g \,\mathrm{sig}(\dot{x}) \qquad (7)$$

shows good agreement with the test result, as seen in Fig.6.

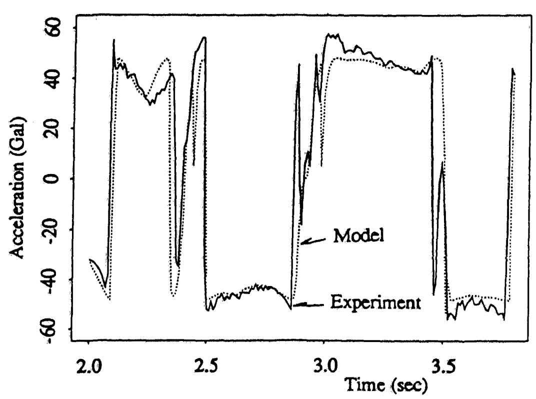

Figure 6. Acceleration Time History

Fig.7 shows the maximum response acceleration, maximum sliding displacement and the residual displacement of the model with passive and hybrid isolation under different intensities of input seismic motions. Hybrid isolation results shown in this figure are under instantaneous optimal control algorithm. It is evident that the hybrid isolation performs better than the passive system in the sense that a reduction of response acceleration has been achieved for small to medium seismic inputs, and at the same time, the excessive sliding displacement under strong earthquake motions is prevented. Furthermore, residual displacement is reduced to almost zero.

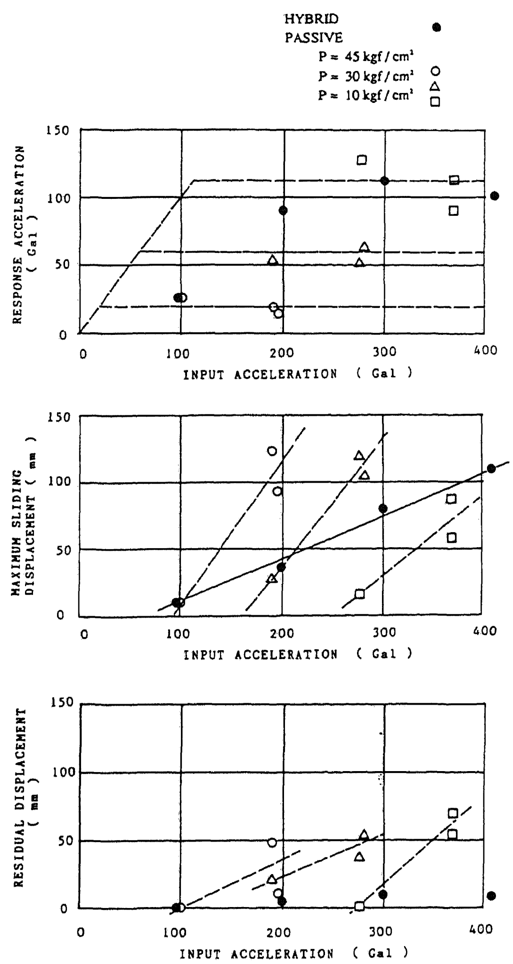

Figure 7. Comparison of Passive and Hybrid Isolation

3. SIMULATION

Numerical simulation of the shaking table tests was conducted, and one of the computed time histories is compared with the test result in Fig.8. This example is a hybrid isolation by the instantaneous optimal control, excited by the El Centro(NS,1940) record, linearly scaled to peak acceleration of 280Gal. The response of the friction to the control signal was computed using Eqs. (4),(5), and (6), with the identified values of the time constant T.

The simulation shows good agreement with the test result as seen in Fig.8. This demonstrates that the analytical model with the parameter values used represents the reality very well.

4. CONCLUDING REMARKS

The following conclusions are obtained from the experimental and analytical studies.

① Significantly beneficial effects of the hybrid control on the reduction of the sliding displacement, residual displacement as well as of the response acceleration, have been verified.

② The hybrid isolation system using the friction controllable bearings appears to be quite robust in the face of uncertainty involved in various aspects of the control model.

③ The computer simulations have good agreement with the experimental results, implying that the analytical model used and the identified parameters represents the actual system very well.

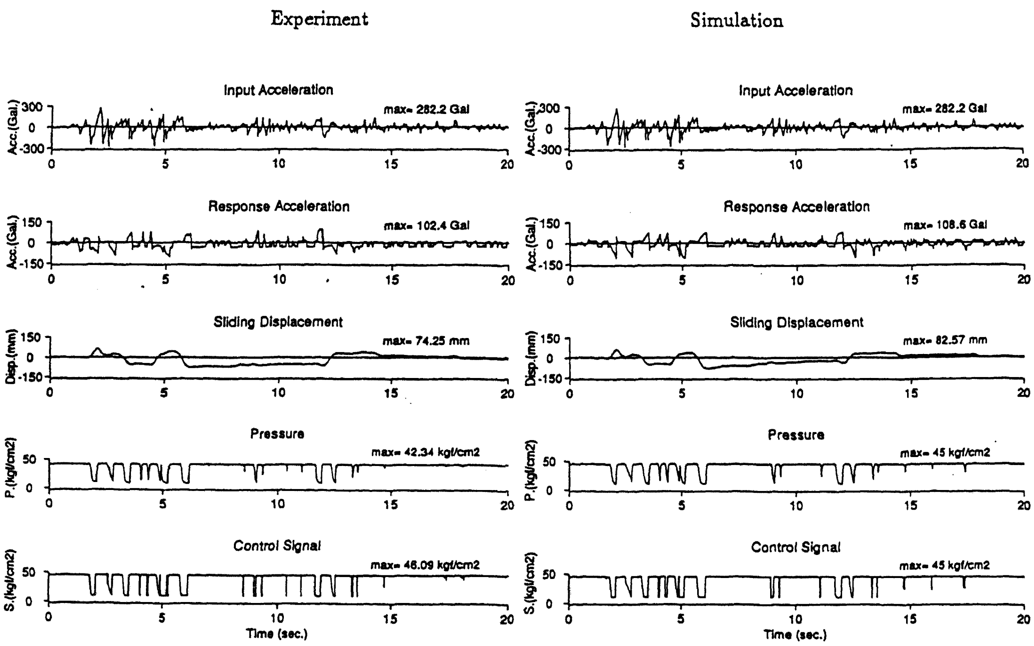

Figure 8. Simulation and Experiment

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