SECTION 5

NUMERICAL SIMULATION

A computer program for the simulation of seismic response of the structure under the hybrid or passive isolation system has been developed. Analytical models presented in the preceding sections, which are based on careful identification experiments, are utilized for computer simulation of experimental results. In this section, it will be demonstrated that these analytical models describe the real system accurately, by carefully comparing the numerical simulation results based on these models with the experimental results.

5.1 Analytical Model and Techniques for Numerical Simulation

The equations of motion of the structural model shown in Eqs. 2.1 - 2.5 and the relationships between the pressure control signal and friction described by Eqs. 4.3 - 4.5 are used for computer simulation. The parameters in these equations use the values given in Table 4.1 as identified by experiments.

Based on the Newmark's β scheme, a double precision FORTRAN routine for numerical integration of the equations of motion and equations of control system has been developed, in which β is selected to 1/6. For the friction system such as under consideration, the precise evaluation are crucial to the accuracy of response calculation when the motion of the structure undergoes transition between the sticking and sliding phases and when the sliding velocity reverses its direction. A time step of Δt is used in the continuous phases of motion, while a much smaller time step Δt is used whenever the phase transits or the velocity reverses its direction. The following computational algorithm is proposed [19] and used.

In Phase II (sliding phase),

1. If the relative velocity of the model changes its direction, go one time interval Δt back, change the time step from Δt to Δt_t and continue the computation again.
2. When the relative velocity changes its direction again, go one time interval Δt_t back, examine whether or not the structural model goes into sticking phase, according to the criterion for transition given in Eq. 2.5.
3. If it goes into sticking phase, change equation of motion to Eq. 2.1, and alter the time step from Δt_t to Δt.
4. If it continues to slide, reverse the direction of friction force, and continue the computation in sliding phase using the time step Δt.

In Phase I (sticking phase),

1. Examine if the model goes into sliding phase according to the criterion given in Eq.

2.3. If it does, change the equation of motion to Eq. 2.2, and change the time step from Δt to Δt_t for the next time interval Δt.

The accuracy of the simulation results is verified by comparing the results with those by finer time steps Δt_t on several simulation cases, and the time step Δt_t has been determined to be 0.00001 sec . The value of time step Δt should be at least 0.002 sec in the simulation of hybrid isolation, because this value was used as the time interval for the measurement of feedback signals in the hybrid control experiments as mentioned before. In the simulation of the response of the building which is passively isolated, however, the value of the time step $\Delta t = 0.01$ sec is used and it appears to be fine enough for the numerical integration.

5.2 Comparison of Simulation with Experimental Results

Shaking table experimental results described in the preceding sections are simulated by numerical analysis. Some examples of time histories from simulation of passive isolation and hybrid isolation using bang-bang control as well as instantaneous optimal control without and with time delay are shown in Figs. 5.1 - 5.4 respectively, together with the corresponding experimental results. In this respect, several remarks seem in order:

1. On the whole, numerical simulation results show remarkably high degree of agreement with experimental results. This demonstrates that the analytical model with the parameter values used represents the reality very well.
2. In simulation, the static coefficient of friction is assumed to be the same as the sliding coefficient of friction. Therefore, simulation could not show the maximum response acceleration, which is due to the static friction, in the passive isolation experiment.

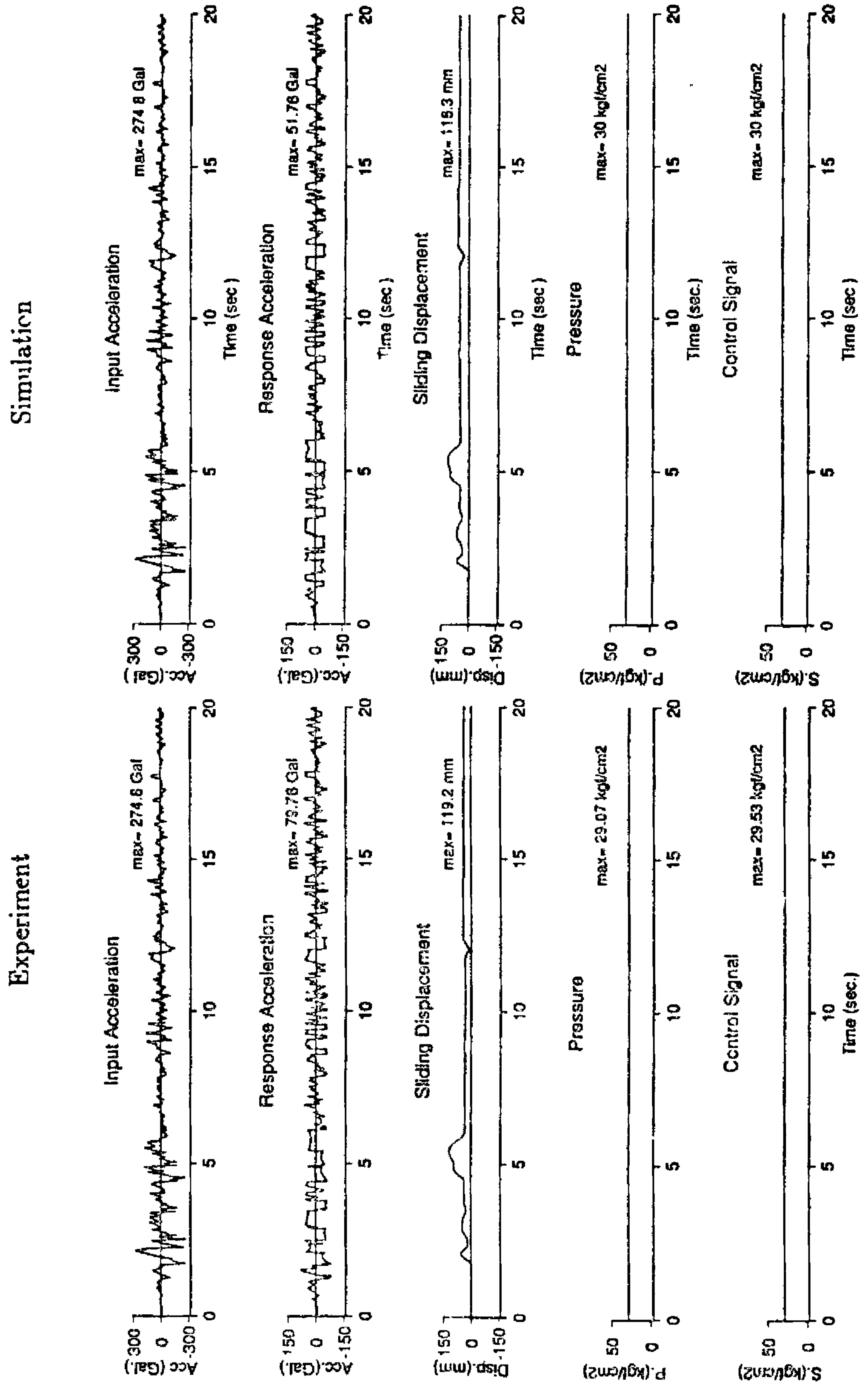

Figure 5.1: Passive Isolation

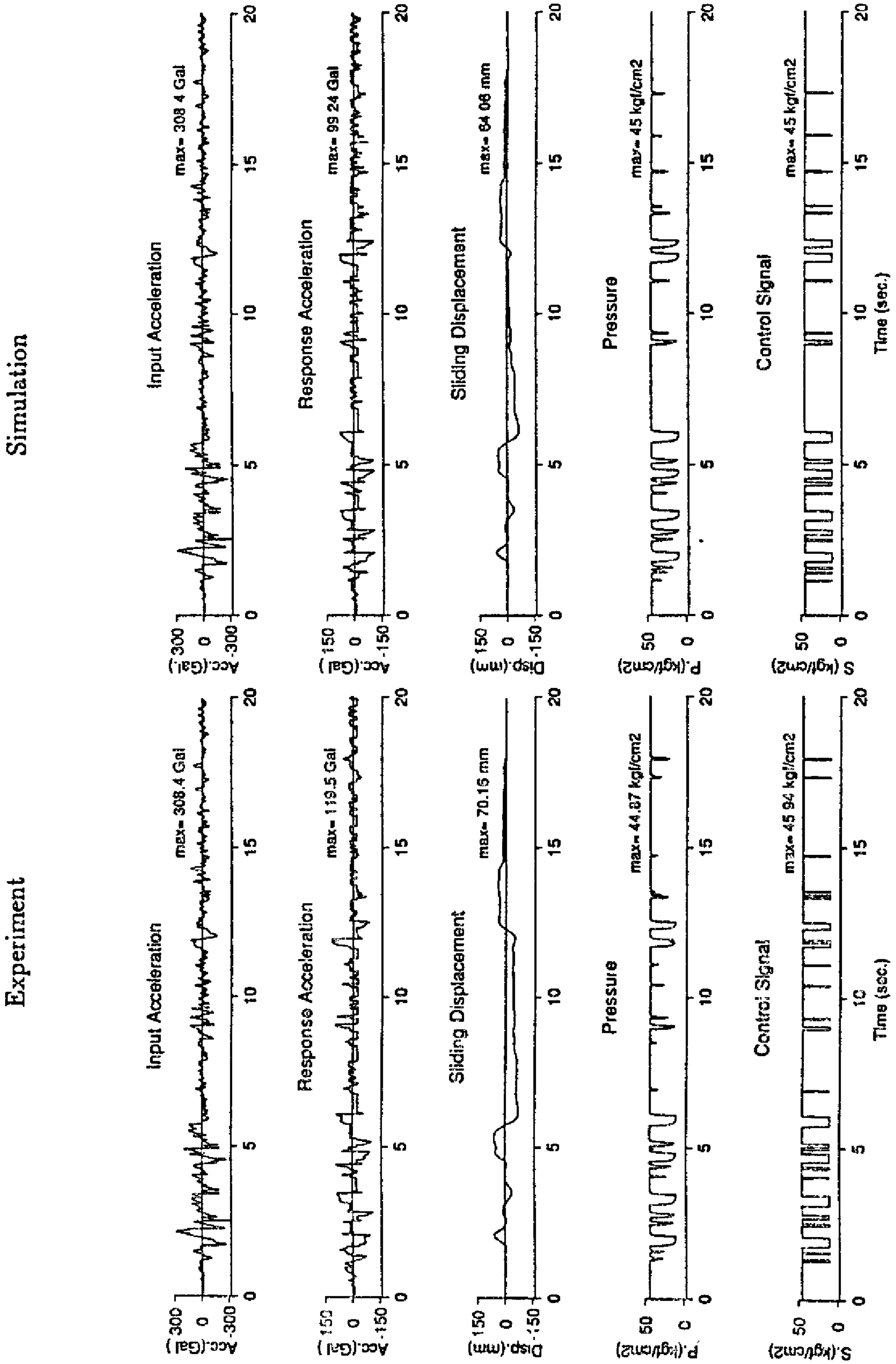

Figure 5.2: Hybrid Isolation under Bang-Bang Control

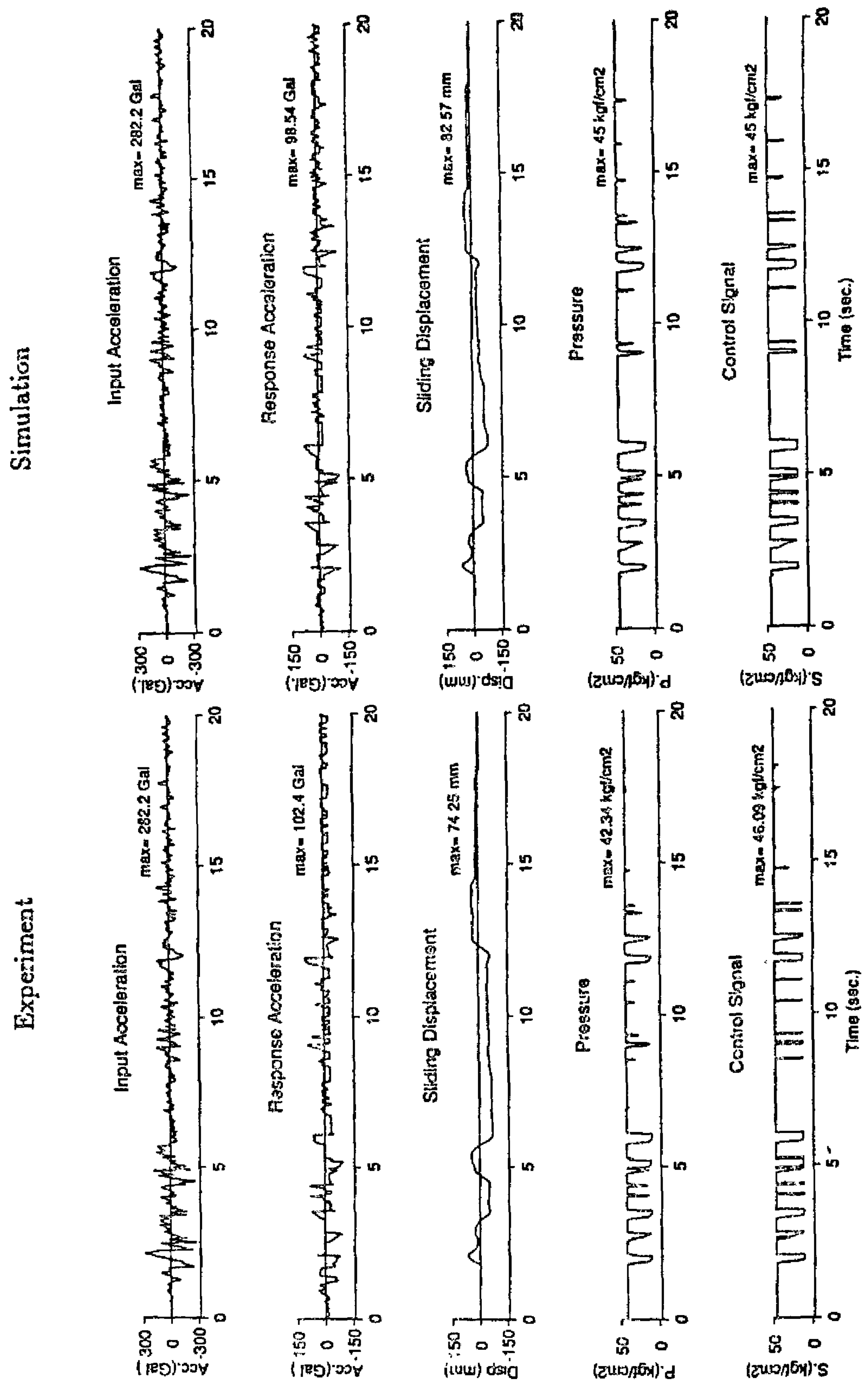

Figure 5.3: Hybrid Isolation under Optimal Control without Time Delay

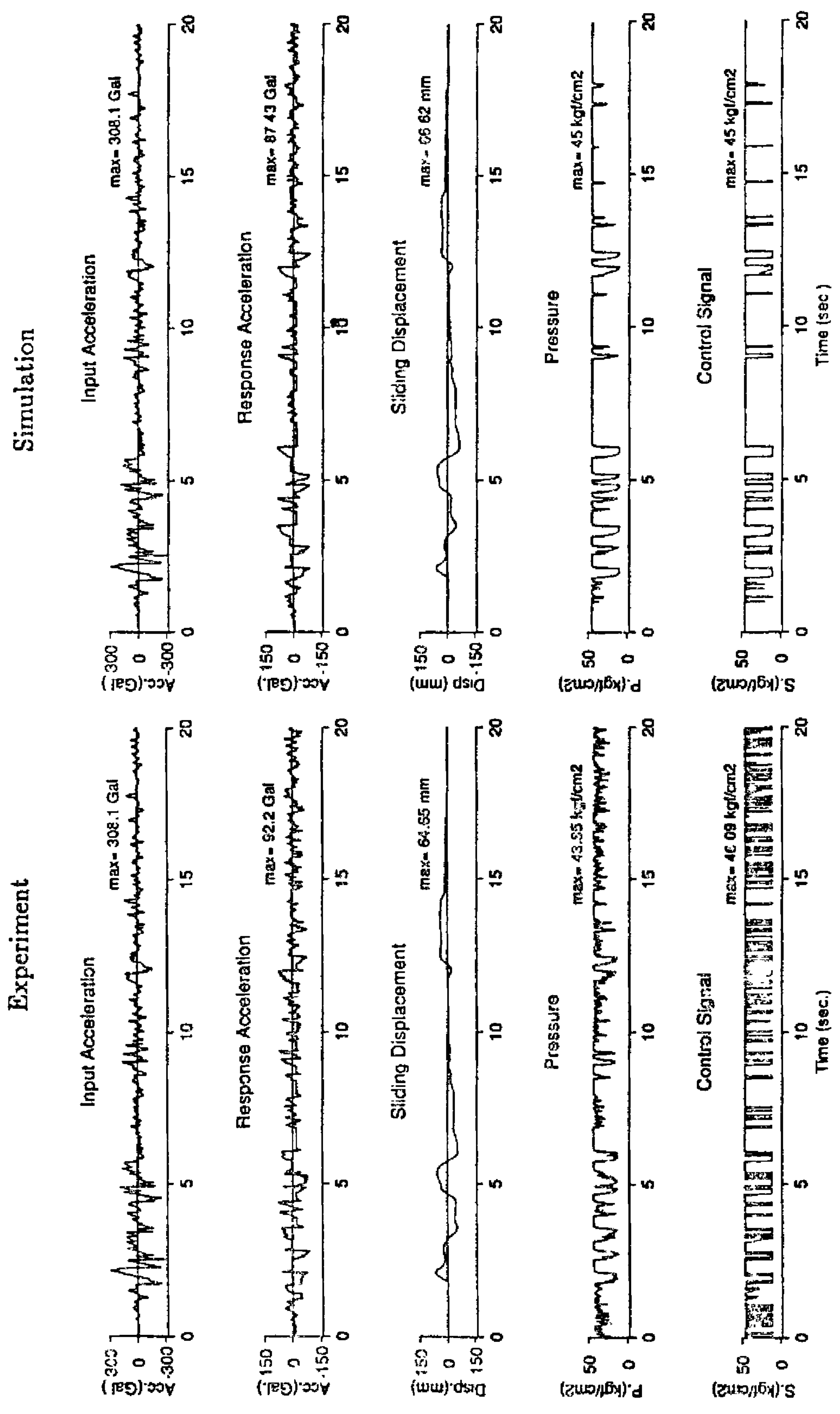

Figure 5.4: Hybrid Isolation under Optimal Control with Time delay

5.3 Robustness of System

In the experiments and computer simulation, it is found that the proposed hybrid isolation system is quite robust.

1. The instantaneous optimal control algorithms in Section 2 are developed on the reduced-order models, ignoring the following aspects in the real models: (i) sticking phase of motion (Eq. 2.1), (ii) influence of sliding velocity on the friction force (Eq. 3.3), and (iii) time delay in the pressure response to the control signal (Eq. 2.6), obviously when developing the algorithm without time delay. However, the reduced-order model did not adversely affect the control performance in a significant way. The so called "control spillover" and instability of the control system were not observed. For example, the comparison between the experimental results of the instantaneous optimal control with time delay (see Fig. 4.10) and without time delay (see Fig. 4.9) showed little difference in the response behavior. This suggests that neglecting the time delay does not degrade the control effectiveness considerably.

2. The time interval of control implementation can be relatively long, as mentioned before.

3. The feedback control signal obtained from the instantaneous optimal control algorithm is not a function of the system parameters, as shown in Eqs. 2.23 and 2.30. Hence, the control efficiency in this case is not affected by paramenter variations.

SECTION 6

CONCLUSIONS

A systematic study on a hybrid sliding seismic isolation system using friction controllable bearings has been presented, including the following aspects:

1. A hybrid isolation system using friction controllable sliding bearings has been proposed for controlling response of a structure subjected earthquakes ranging from small to large intensities.

   This hybrid isolation system also has the following general advantage: the system requires smaller amounts of energy and power than the corresponding actuator-controlled system, and as a consequence, the use of accumulators for the source of energy is possible, thus eliminating the necessity of an emergency energy supply system.

2. Control algorithms, instantaneous optimal control and bang-bang control have been developed for controlling the friction force in the hybrid sliding isolation system. Standard control theory is difficult to apply in a straightforward fashion, in this case where the control force has a nonlinear feature.

3. A prototype hybrid sliding isolation system using friction controllable bearings has been physically developed, and shaking table experiments were performed on a rigid structural model equipped with such a hybrid system. A computer code has been developed for real-time on-line control implementation. The dynamic characteristics of the control system between bearing pressure and sliding friction have been identified. The results of hybrid sliding isolation experiments were compared with those of passive isolation.

4. Computer codes for the simulation of structural response under passive or hybrid control have been developed, and simulation analysis has been performed. The numerical results have been compared with experimental results.

Through the experimental and analytical study, the following conclusions have been obtained:

1. Significant advantage of the proposed hybrid sliding isolation system has been demonstrated: (1) for the small to medium earthquakes, the friction is controlled to make the structure slide easily to reduce the transfer of the seismic force to the structure to a minimum; (2) As the input earthquake becomes more intense, the friction is controlled to confine the sliding displacement of the structure to an acceptable range, while at the same time to keep the transfer of seismic force as small as possible. Such intelligent features of the friction controllable hybrid system does make the conventional passive sliding isolation system effective for all intensities of earthqukes.

2. Control algorithms developed for control of nonlinear friction force proved to be effective in achieving the desired control performances. In addition, they are practical and

easy for real-time on-line control operations.

3. The analytical model of dynamic characteristics between the bearing pressure control signal and the friction on the sliding interface has been identified. Computer simulation results excellently match the experiments. This implies that the analytical model represents the actual system very well, showing the possibility of utilizing the model to perform analytical study on other types of real structures equipped with the hybrid isolation system under different earthquake conditions.

4. The hybrid sliding isolation system appears to be quite robust, demonstrating the high potential for the application of the system to actual structures.

In the immediate future, possible implementation of the hybrid sliding isolation system to existing full-size structures such as buildings and girder bridges will be explored.

SECTION 7

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