Earthquake Engineering, Tenth World Conference © *1992 Balkema, Rotterdam. ISBN 90 5410 060 5*

Hybrid control of sliding structures

Sohail M.Qureshi
NESPAK, Lahore, Pakistan

H.Tsutsumi & S.Kitagawa
Kyushu University, Fukuoka, Japan

S.Adachi & Y.Fujio
CTI Engineering, Fukuoka, Japan

ABSTRACT: This study is concerned with the experimental and analytical aspects of actively controlled pure friction (P-F) based structures with and without active feedback control. One of the objectives is to find the dynamic characteristics of a hybrid system especially for those having low mass-ratio, so that stable performance results can be obtained near its natural frequency. The first aspect of the research centers around evaluating the frictional properties of Teflon interfaces under a rigid mass vibrating system. The experimental and analytical studies show that the spectral response of sliding structures is quite independent of the excitation frequency. Moreover, the response amplification is quite sensitive to the system damping and the system gain matrix. The controlled response is calculated using the concepts of stick-slip phases and a modification of the system gain is carried by an extended least-square scheme.

1 INTRODUCTION

Conventionally designed structures could be significantly damaged if the induced energy exceeds the hysteretically dissipated energy capacity. This paper describes the sliding dynamic characteristics of Teflon and its use in the active control of hybrid structural systems. It is concerned with the evaluation of the frictional properties of Teflon interfaces and the response of a rigid mass vibrating system isolated by such devices to linearly varying steady excitation. Analytical studies were also carried out to find the effects of random base excitation on the sliding displacement of the rigid mass to help decide the design bearing pressure and the associated sliding coefficient of friction.

Experiments on a rigid mass model were conducted to find the effects of bearing pressure, shaking frequency and excitation amplitude on the sliding coefficient of friction, mass acceleration, sliding displacement and the residual sliding displacement. Experiments were also conducted on a two degree of freedom frame model and tested for sliding response, as well as its control with the proof mass actuator (PMA). The proof mass characteristics, system damping and system parameters were evaluated initially for use in the simulation studies. The sliding frame response to random excitation and feedback was experimentally recorded. The response is calculated using the concepts of stick-slip phases. The controlled response is then computed by modifying the system gain matrix.

2 RIGID MASS EXPERIMENT

The rigid mass model was supported on unfilled Teflon elements sliding on a 5 mm thick Teflon sheet. All experiments were excitation controlled and conducted at input frequencies of 1.5, 2.0, 3.0, 4.0 and 5.0 Hz up to either 0.50 g or the displacement limit of the shake table. All tests were repeated for bearing pressures of 1.31, 2.19, 3.02, 4.08, 6.45 and 7.99 MPa. The maximum velocity of excitation was between 1.5 and 26 cm/s.

Fig. 1 shows the results of rigid mass vibrating system where the bearing pressure was varied and the input excitation was increased from 0~500 *gal*. Recordings were made for absolute and relative mass displacement, and for absolute and relative mass acceleration at each bearing pressure. Fig. 2 shows the effect of the frequency of excitation for 3.02 MPa. In this case the initial coefficient of friction when the mass detaches itself is between 0.065 ~ 0.085. The coefficient of sliding friction seems to decrease with increasing frequency of the excitation, though this was not very clear for lower values of the bearing pressure. This decrease is perhaps due to the heating effect associated with increased cycles of sliding. An average value of $\mu_{sliding}$ has been used in the Coulomb model. Fig. 3 show the effect of the ex-

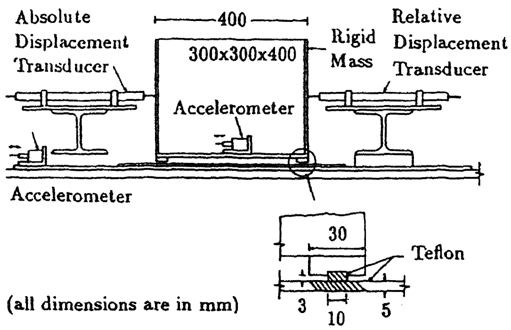

Figure 1. Rigid Mass Model

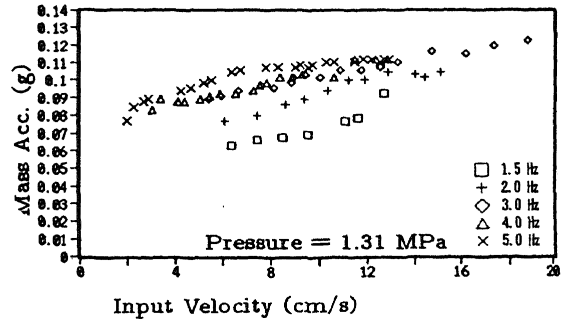

Figure 4. Effect of Frequency on Mass Velocity

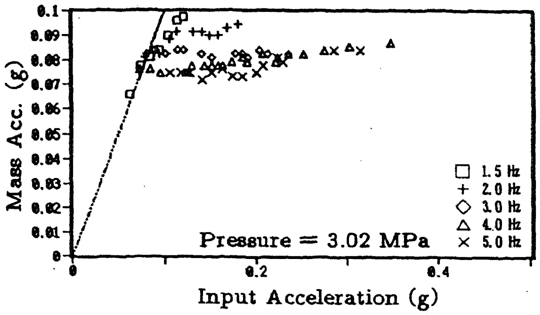

Figure 2. Effect of Frequency on Mass Acceleration

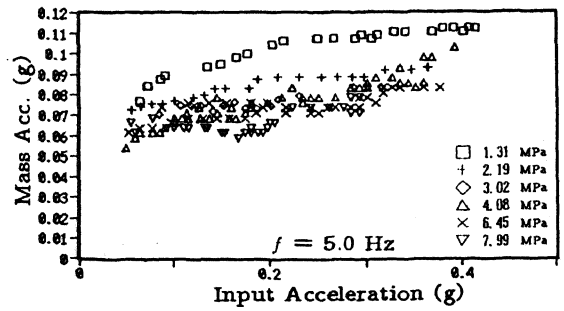

Figure 5. Effect of Bearing Pressure on Mass Acceleration

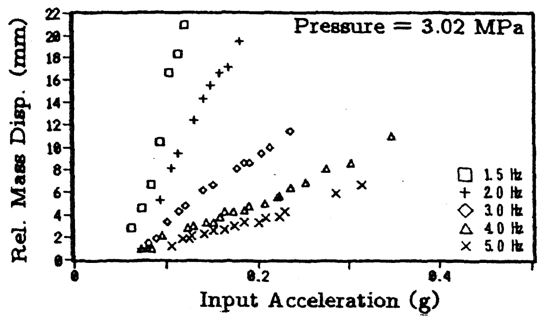

Figure 3. Effect of Frequency on Relative Mass Displacement

citation amplitude on the relative mass displacement for the 3.02 MPa bearing pressure. The relative mass displacement shows a linear variation with increasing amplitude of the excitation at each frequency. Also the relative mass displacement is greater for the higher bearing pressure than the lower bearing pressure. This fact too should be considered in the actual design.

Fig. 4 shows the effect of excitation velocity on the absolute mass acceleration. This shows two distinct features, (1) the initiation of sliding has a definite relationship with the velocity of sliding at each frequency. This velocity seems to decrease with increase in the frequency of excitation and at a constant kinetic energy for 1.31 MPa, (2) the coefficient of sliding friction tends to be constant beyond 10 cm/s ~ 20 cm/s for all frequencies and is expected to reach a constant value.

Fig. 5 shows the effect of bearing pressure on the mass acceleration. The absolute mass acceleration tends to be constant with increasing amplitude of the excitation for all pressures. The maximum absolute mass displacement is observed to vary between 2 mm for high pressure and 3 mm for low pressure, which could be considered quite small. It should, however be kept in mind that this is a short period excitation and large absolute displacements are a result of long period motions. The relative displacement at large amplitude of excitation was also accompanied by a twisting or bi-directional motion of the rigid mass. The coefficient of friction decreases with an increase in the bearing pressure, a result that is opposite to the predictions by the elastic theory of friction.

Fig. 6 shows the results for the absolute mass displacements. These results are for the Coulomb model using an average value of the dynamic coefficient of friction μ_d of 0.09. These results are

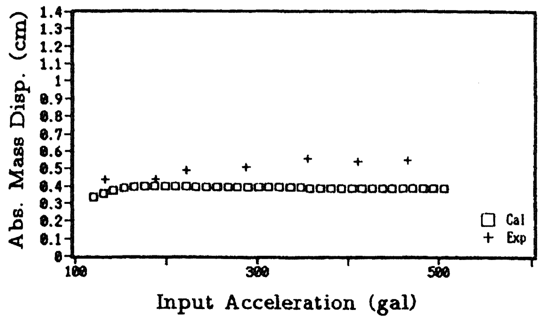

Figure 6. Comparison of Absolute Mass Displacement

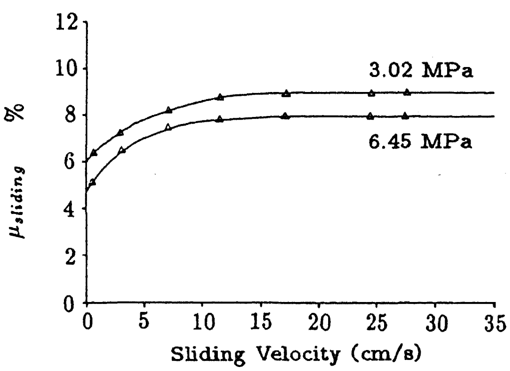

Figure 7. Effect of Sliding Velocity on $\mu_{sliding}$

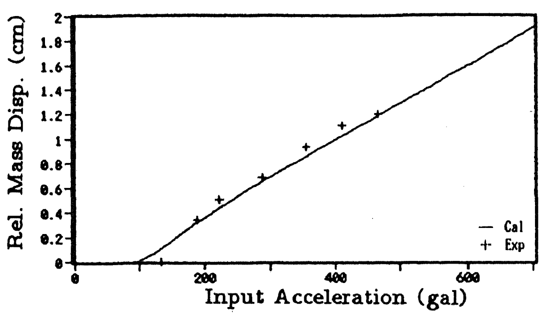

Figure 8. Comparison of Relative Mass Displacement

for 1.31 MPa at 3 Hz frequency of the excitation. Coulomb model shows a perfect match of the relative mass displacement values, but predicts a smaller absolute mass displacement than the experimental value, though the results are within 20 %.

The Teflon interfaces maintained an initial sticking mode until the amplitude of acceleration was greater than μg to start a continuous slip-slip motion (except for an instantaneous sticking when the sliding velocity reversed in direction).

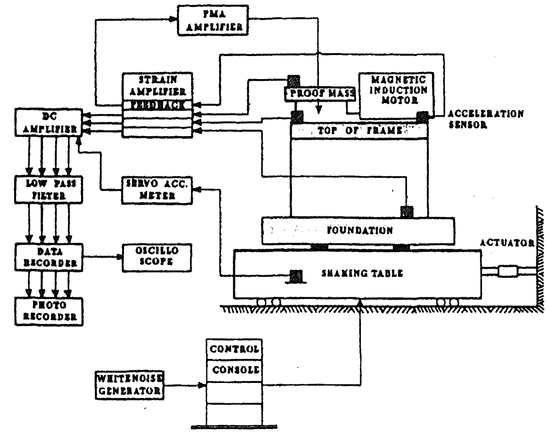

Figure 9. Experimental Set-up

But the behaviour is contradicted by the prediction of Coulomb theory for stick-slip motion between $0.537 < \mu g/a_0 < 1$, where a_0 is the acceleration amplitude of the sinusoidal shaking. Due to continuous sliding and slip-slip tendencies of the Teflon interfaces, this experiment shows positive results of transmitting no high frequency response to the mass.

The main feature of the mathematical model used is the dependence of the frictional force on the velocity of sliding and the bearing pressure. $\mu_{sliding} = f_{max} - (\delta f)\exp(-q|\dot{u}|)$, where f_{max} is the coefficient of friction at large velocity, δf is the difference between the initial coefficient of sliding friction and f_{max}, $\dot{u}$ is the sliding velocity, and q is a constant for a certain bearing pressure. This model differs significantly from the simpler Coulomb model. Though results indicate that Coulomb theory may provide close estimates of the response. However, the response contains high frequency components, which are absent from the experimental model.

The variation of the $\mu_{sliding}$ is adjusted for the bearing pressure and the normal force at the interface is updated at every step. The effect of the bearing pressure is included by interpolating and continuously modifying f_{max} and δf. The changes in bearing pressure could be large, when the effects due to the vertical component of the earthquake motion are included. Another factor of concern causing the bearing pressure fluctuations is the overturning moment in slender structures.

Fig. 7 shows the result of the variation of the sliding coefficient of friction with the velocity of sliding for 3.0 Hz frequency and for cases 3 and 5. The experimental and analytical results compare quite well showing the accuracy of the model. Fig. 8 shows a comparison of the relative mass displacement for the experimental results and the non-coulomb model for a frequency of

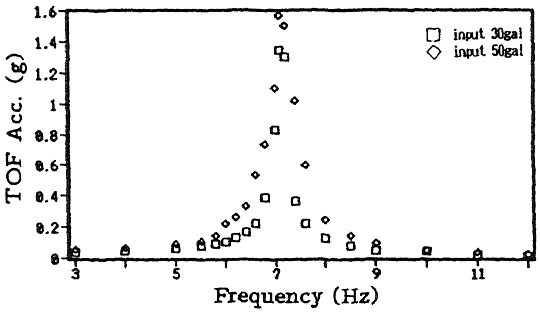

Figure 10. Frequency Response Curves for Fixed Base Frame

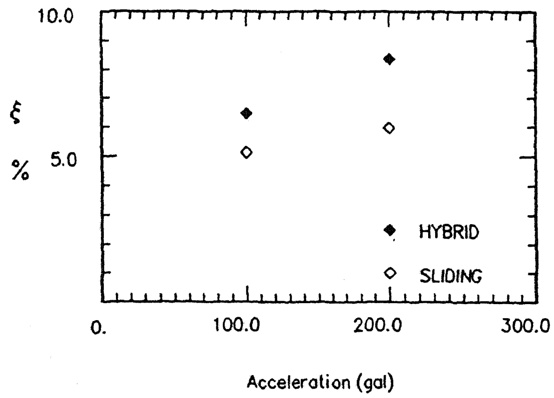

Figure 11. Free Vibration Test Results

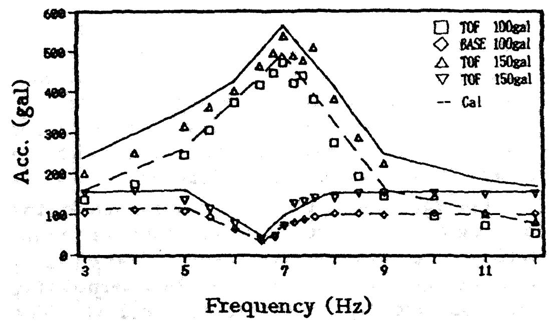

Figure 12. Frequency Response Curves for Sliding Frame

3.0 Hz in case 1. The value of q varies between 0.18 ~ 0.27 for all the six cases. Details of the analytical model are already given in Qureshi et. al., (1991).

3 HYBRID SEISMIC RESPONSE CONTROL

Active Seismic response control can be based on the following: (i) by stopping the seismic energy transmission, (ii) use an energy absorption mechanism, (iii) isolate the natural frequencies of the controlled structure from the predominant ground motion frequencies, and (iv) control a structure by creating non-resonant, nonstationary states through the structural parameters adjustment. Based on the above notions and knowing that, the ground motion being a nonstationary phenomenon intuitively gives rise to a new control approach. The input energy can be significantly reduced if the natural frequencies of the structure are dynamically varied such as not to pass through the peak power of the ground motion. In such a situation a counter force can be used to artificially modify to a non-resonant state.

A practical structural control approach utilizing the dry friction isolation and active control force to minimize the first mode accelerations by a direct acceleration feedback has been experimentally and analytically implemented. Here we would like to call it a 'hybrid active control approach'. It is to be emphasized that the time delay involved in this control system is only the time constants of the acceleration feedback sensors and those of the proof mass actuator (PMA). The maximum control force equals the magnitude of the disturbing force transmitted to the base and the top floor after isolation times an acceleration gain.

4 HYBRID FRAME EXPERIMENT

Fig. 9 shows the experimental set up with the *direct acceleration feedback arrangement and the* PMA. The model is a steel frame 424 *mm* wide and 167 *mm* high. The top mass is 16.2 *kg* and the foundation mass is 26.7 *kg*. Four Teflon bearings resulted in a pressure of 1.1 MPa. The experimental sequence was divided into five cases, (1) PMA characteristics, (2) system damping and stiffness parameter evaluation, (3) response of sliding frame to base excitation, (4) response of sliding frame to base excitation and PMA control force, (5) response of sliding frame to random excitation with and without acceleration feedback. Tests were carried out at a base excitation amplitude of 30, 100 and 150 *gal* and at frequencies between 3 ~ 12 *Hz* so as to generate the frequency response data. Recordings were also made to ascertain the experimental phase changes at each frequency.

The PMA was adjusted to produce the opposite inertial force relative to the first story except near sudden phase changes. The damping ratio of the fixed base frame by the half-power method was evaluated to be 1.8%. The case 2 results shown in Fig. 10 indicate the resonant frequency of 7.1 Hz and the maximum response acceleration of 1340 gal for 30 gal and 1540 gal for 50 gal input excitations. The large amplification of the response is due to low structural damping already reported. A further insight is the fact that a large control force would be needed to suppress the vibrations of the fixed base frame, which becomes impracticable for large structures. This necessitated the implementation of Teflon sliding bearings and the active mass control for two main reasons, (1) to attenuate the response accelerations, and (2) to practically control the response by the application of the weak control forces in the neighborhood of the resonance condition. The free vibration tests were also conducted to find the value of the actual structural damping ratio for the sliding and the feedback conditions. These values for the input amplitudes of 100 and 200 gal are shown in Fig. 11.

Fig. 12 shows the Teflon mounted structure's frequency response characteristics. The 100 gal input does not shift the natural frequency, but attenuates the peak acceleration. This could be explained by the sliding initiated close to the resonant frequency, isolating the model, but not altering its structural parameters. Whereas the 150 gal input produces the continuous slip state between 5.0 and 8.0 Hz by taking advantage of the Teflon's isolation characteristics. The peak response is substantially reduced in comparison to the fixed base structure, and a second peak in the natural frequency of 7.8 Hz is also observed, perhaps due to the mass-ratio effect. The response of the foundation shows an interesting feature of reducing below the peak input amplitude and exposing the sliding region. The solid and the dotted lines show the results of the response evaluation for 150 and 100 gal input excitations by the already explained concepts of the stick-slip phases. Results are shown for the base and the TOF responses. The excellent match validates the formulations; for details see Qureshi et. al., (1992).

Fig. 13 shows the frequency response curves for the case 4 with the application of the proof mass feedback control force. The response is quite similar to the sliding frame response except a reduction in the natural frequency in the vicinity of 6.0 Hz due to the PMA characteristics already explained. The significant effect of the control force on the peak response acceleration is observed for the large input accelerations and near the resonance frequency. The plot of the foundation response does not seem to vary in form when compared with that of the sliding response though the reduction trough has moved towards 5.0 Hz. The responses calculated by the system gain modification and the extended least square procedure along with the stick-slip concepts predict the near perfect experimental results. Table 1 summarizes the experimental results for the three cases of the response conditions, i.e, the

Table 1. Harmonic Response Summary

ACC. (gal)	INPUT	CASE 1	CASE 2	CASE 3
Relative	30	1340	300	230
Maximum	50	1540		
	100		400	240
	150		460	260

Case 1: Fixed Base Frame
Case 2: Sliding Frame
Case 3: Hybrid Frame

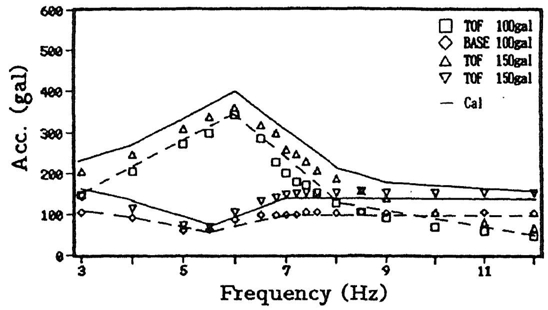

Figure 13. Frequency Response Curves for Hybrid Frame

fixed base frame, the sliding frame and the hybrid frame responses. A large reduction in the relative response peaks for the sliding frame and then a further reduction of 43% for the hybrid frame is observed.

The arrangement for carrying out the random excitation and feedback is the same as for the sinusoidal excitation except with the addition of the white noise generator. A peak random shaking acceleration of above 150 *gal* input for the sliding and the feedback frame was used. A comparison of top of the frame response for the sliding and the hybrid frame shows a reduction in the peak response of the order of 35%. The response acceleration and displacements for the El-Centro NS component show a reduction of 46% for the TOF response. Some of the earthquake response results are summarized in Table 2. Significant reduction in the TOF displacements and the sliding displacement is also observed. Such a system with small proof mass is extremely robust and useful in attenuating the responses at resonance.

5 CONCLUSIONS

1. The coefficient of friction decreases with increases in the bearing pressure and the rate of reduction is dependent on the sliding velocity.
2. The sliding system at low bearing pressures undergoes smaller base displacements than at the high pressure. A reasonable coefficient of

Table 2. Earthquake Response Summary

EARTHQUAKE	Peak Acc.	Sliding		Hybrid		Reduction
	g	Base	TOF	Base	TOF	%
El-Centro	0.339	900	1300	650	700	46
Olympia	0.142	135	400	130	300	25
Taft	0.179	145	400	150	250	37
Miyagi-Oki	0.306	730	1000	240	750	25
Dorokodan-1	0.104	105	305	105	240	21
Nihonkai-Chubu	0.136	115	500	100	390	22
Artificial E.Q.	0.150	190	590	160	380	35

all response in gal

sliding friction for actual use is 0.10 which in this case translates to a pressure of about 1.0 MPa.

3. A hybrid system with closed-loop feedback proof mass control is necessary to reduce the response at the natural frequency of the sliding structure, especially for low mass-ratio systems. The spectral response of sliding structures is, for most cases quite independent of the excitation frequency. Moreover the response amplification is quite sensitive to the system damping.
4. When the structure is isolated, the relative displacement of the top mass decreases and as such a small proof mass could further reduce the response acceleration near the resonance condition. A reduction of up to 40% in response is obtained for the feedback controlled proof mass. The system covariance or gain matrix can be used in evaluating the feedback controlled response.
5. The inability to pre-assess the predominant earthquake frequencies and peak amplitude warrants active control mechanisms as the one proposed, to be used in addition to the base-isolation for enhancing and modifying the structural parameters, and to adapt to the needs of extra energy absorption and dissipation. Such systems could find application in certain special situations, such as nuclear power plant components.

REFERENCES

Kobori, T., Kanayama, H., and Kamagata, S. 1989. Active Seismic Response Control Systems for Nuclear Power Plant Equipment Facilities. Nuc. Eng. and Des., Vol. 111: 351-356.

Qureshi, S. M., Uno, K., and Tsutsumi, H. 1991. Vibration Control of Pure Friction Based Rigid Structures under Strong Earthquake Motions. Memoirs of the Faculty of Engineering, Kyushu University, Vol. 51-4, No. 4: 263-291.

Qureshi, S. M., Uno, K., and Tsutsumi, H. 1992. Hybrid Control of a 2DOF System on Sliding Friction under Strong Earthquake Motions. Memoirs of the Faculty of Engineering, Kyushu University, Vol. 52-1, No. 1: 21 pages.

Wen, Y. K. 1976. Method for Random Vibration of Hysteretic Systems. Proc. ASCE, Vol. 102, No. EM2: 249-263.

Westermo, B. and Udwadia, F. 1983. Periodic Response of a Sliding Oscillator System to Harmonic Excitation. Earthquake Engineering and Structural Dynamics, Vol. 11: 135-146.