OPTIMUM CHARACTERISTICS OF AN ELECTROMECHANICAL EARTHQUAKE ISOLATION SYSTEM

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SUMMARY

The performance of a semi-active earthquake isolation system is discussed. The system is proposed for the protection of sensitive equipment for which passive isolation is insufficient. The system requires a small amount of electric battery power. Hybrid computer simulations of the proposed system indicate that protection factors (ratio of peak acceleration response of non isolated system to that of isolated system) of 40 can be achieved for typical earthquakes. The simulations were conducted with families of artificial earthquakes having well defined statistical properties. Preliminary design charts are presented and potential applications are discussed.

INTRODUCTION

The seismic response of a structure or a component inside a structure can be reduced by passive or active isolation. Passive isolation, in the form of a soft story (1), roller supports (2), steel dampers (3), neoprene pads (4), etc. is dependable and maintenance free. The efficiency of passive isolation is, however, limited. To achieve greater isolation performance, active isolation devices could be used. Such devices need an external power source to produce the forces or displacements which counteract the action of the earthquake. Active devices are commonly used in the aerospace or naval fields for vibration isolation (5,6), but, because of their complexity and need for external power and continued maintenance, they are unlikely to be used in seismic applications.

Recognizing both the performance benefits as well as the limitations of passive or fully active systems, a semi-active earthquake protection device has been developed (7). A somewhat similar concept has been proposed for vibration control (8). The device requires a small amount of electric power to operate its control system and its servo valve. Such power would be available from emergency batteries.

SEMI-ACTIVE ISOLATION SYSTEM

Passive isolation schemes for a rigid structure using a combination of rollers, spring and damper or neoprene pads are shown in Fig. 1.a and b. The idealized semi-active device proposed herein is shown

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in Fig. 1.c and also, in more details, in Fig. 2. X_g and X_a define the absolute positions of the ground and the isolated mass, X_p is the displacement of the piston P relative to the center of its cylinder and X_s is the elastic stretch of the spring K.

The piston P divides the cylinder into two oil filled chambers. The movement of the piston is, therefore, restricted by the ability of the oil to flow through the feedback pipe cdef or in and out of the ports a and b. The ports a and b communicate with a separate hydraulic system which keeps the piston centered in everyday conditions and brings it back to that center position after an earthquake. During an earthquake, the ports a and b are closed. Therefore, the movement of the piston is controlled by the relationships between the areas of the piston, A_p, the feedback pipe, A_c and the valve opening, A_v, and the properties of the oil as it is throttled through these openings.

If the valve is closed, the semi-active device provides a rigid connection between the ground and the spring-damper link to the mass M. If the valve is partially or fully opened, the connection is partially removed and energy is dissipated as the oil is forced from one chamber to the other. If the piston cone h engages into the end chamber g, passive cushioning is provided.

With minimizing the maximum acceleration response $\ddot{X}_{amax}$ as the objective, a simple control strategy based on a fully opened or closed valve is shown in Fig. 2. While not necessarily optimum, the proposed strategy is simple and very efficient. The valve opens if the piston is off-center and the seismic forces tend to push it back toward the center. This "borrowing" of energy from the earthquake at judicious times prevents excessive drifting of the piston and its loss of function as it reaches the end of its available stroke. The valve opens if the acceleration response exceeds a threshold value $\ddot{X}_{alim}$.

To evaluate the performance of the proposed system, extensive hybrid (combined analog and digital) computer simulations have been performed. These simulations were based on the following mathematical model of the isolated system.

Continuity requires that

$$X_a = X_g + X_p + X_s + \text{Constant} \qquad (1)$$

$$\dot{X}_a = \dot{X}_g + \dot{X}_p + \dot{X}_s \qquad (2)$$

$$\ddot{X}_a = \ddot{X}_g + \ddot{X}_p + \ddot{X}_s \qquad (3)$$

The inertial force on the isolated structure is equal to the total force across the spring-damper link and also equal to the force on the piston. Therefore,

$$\ddot{X}_a = w^2 X_s + 2\xi w X_s \qquad (4)$$

and

$$\ddot{X}_a = -(A_p/M)\Delta P \qquad (5)$$

where w and ξ are the natural frequency and fraction of critical damping of the system when the piston is locked, and ΔP is the pressure differential between the right and left chambers. Since the device is an energy dissipator, ΔP is a function of the piston velocity $\dot{X}_p$. Using the square law of throttled fluids,

$$\Delta P = \frac{1}{2}\,\rho\,(k_t+k_v)\left(\frac{A_p}{A_c}\right)^2 \dot{X}_p^2 \qquad (6)$$

where ρ = mass density of oil

$$k_t = \text{constant} \simeq \left(1 - \frac{A_c}{A_p}\right)^2 + \left(1 - \sqrt{\frac{A_c}{A_p}}\right)/2$$

k_v = constant function of valve opening A_v

To solve Eqs. 1 to 6 simultaneously on the analog computer, scale factors of S_o/w, S_o, and $S_o w$ are applied to displacements, velocities and accelerations, respectively. If $\ddot{X}_{gmax}$ is the maximum expected ground acceleration, S_o is conveniently taken as $\ddot{X}_{gmax}/w$. Eqs. 5 and 6 are combined and rearranged to give

$$\left[\frac{\dot{X}_p}{S_o}\right] = -\,\text{sign}\,[\ddot{X}_a]\; S_1\, S_2 \sqrt{\frac{|\ddot{X}_a|}{S_o w}} \qquad (7)$$

where $S_1 = \sqrt{\dfrac{k_t}{k_t+k_v}}$ and (8)

$$S_2 = \sqrt{\frac{2Mw}{A_p\,\rho}\left(\frac{A_c}{A_p}\right)^2 \frac{1}{k_t}\,\frac{w}{\ddot{X}_{gmax}}} \qquad (9)$$

The non-dimensional parameter S_1 in Eq. 8 is related to the valve opening A_v. $S_1 = 0$ if the valve is closed and $S_1 = 1$ if it is fully opened. To account for the finite response time of the valve, 0 to 1 changes in S_1 (or 1 to 0 changes) have been programmed to occur linearily over periods of 50 milliseconds.

Since Eqs. 1, 2, 3, 4 and 7 completely describe the behavior of the isolation system, and since S_1 can be removed as a parameter (see above discussion), S_2 appears as the fundamental non-dimensional parameter controlling the performance of the device.

RESPONSE SIMULATIONS

A parametric study of the performance of the proposed system was conducted by subjecting it to artificial earthquakes having a response spectrum closely matching that expected at the Oak Ridge (USA) site. The hybrid computer technique used to generate these synthetic earthquakes is described in Ref. 9. Twenty earthquakes were thus generated and stored in digitized form. Then, for a given set of values of w, ξ, S_2 and $X_{alim}/\ddot{X}_{gmax}$, twenty responses were calculated and statistics of peak response accelerations $\ddot{X}_{amax}$ and peak piston displacements X_{pmax} were collected. In addition to storing the earthquake and the response data, the digital portion of the hybrid equipment was used to control the valve. The differential equations were solved on the analog equipment. Responses to 30 sec. earthquakes were obtained in real time, that is in 30 sec. A typical simulation run can be seen in Fig. 3. Fig. 4 shows the mean and the mean plus one standard deviation of the ratio $\ddot{X}_{amax}/\ddot{X}_{gmax}$ for a passive isolation system. Corresponding results are shown in Fig. 5 for the semi-active scheme with maximum piston displacements shown in Fig. 6. In Figs. 5 and 6, the threshold limit was set up at $X_{alim} = .1\ \ddot{X}_{gmax}$. It can be seen that the semi-active system performance is significantly better than that of the passive system.

The information in Figs. 5 and 6 can be used for preliminary sizing of the device. Assume the following data: weight of mass to be isolated = 100 tons; $\ddot{X}_{amax} = .05g$; $\ddot{X}_{gmax} = .3g$; maximum operating pressure of oil = 500 psi. Enter Fig. 5 with $\ddot{X}_{amax}/\ddot{X}_{gmax} = .167$ and and arbitrary $S_2 = 2$ to read w = 7 rad/sec. Then enter Fig. 6 with $S_2 = 2$ and w = 7 to read $X_{pmax}g/\ddot{X}_{gmax} = 2$. Therefore, $X_{pmax} = .6$ ft, requiring a total piston stroke of 1.2 ft. Other values of S_2 would have yielded different w and stroke requirements. From the maximum force on the piston, $M\ \ddot{X}_{amax}$, and the maximum operating pressure, get the piston area $A_p = 20\ \text{in.}^2$. Finally Eq. 9 can be solved for A_t to give $A_t = .09\ \text{in.}^2$

SUMMARY AND CONCLUSIONS

The proposed semi-active earthquake isolation system is very efficient. It may be used to protect equipment directly or to isolate entire rooms or portions of buildings containing delicate equipment. Maintenance on such a system should not exceed that required on elevators or other mechanical devices. Some economy might even be achieved if the cost of the system is more than offset by the savings from reduced acceleration requirements on the equipment. Another promising application is in the isolation from vertical accelerations, an impossible task with currently available passive systems.

Additional work is needed to investigate the performance of the semi-active device with flexible structures. Prototype isolators tests on a shaking table would be needed to build confidence in the proposed scheme.

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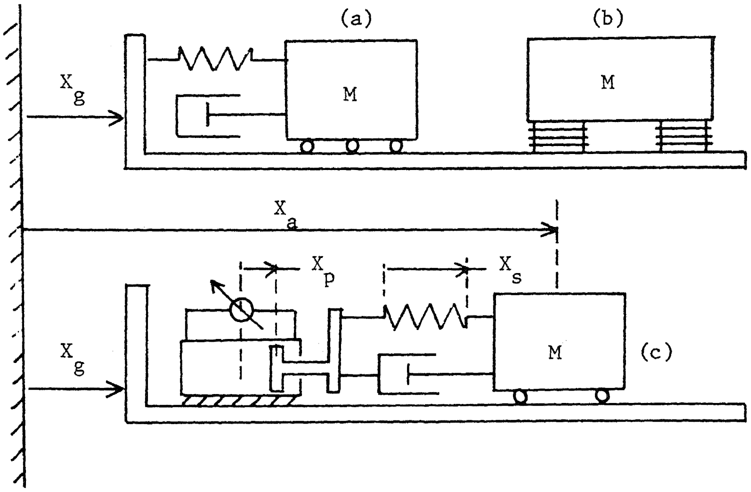

Fig. 1. Passive (a and b) vs. active (c) earthquake isolation systems

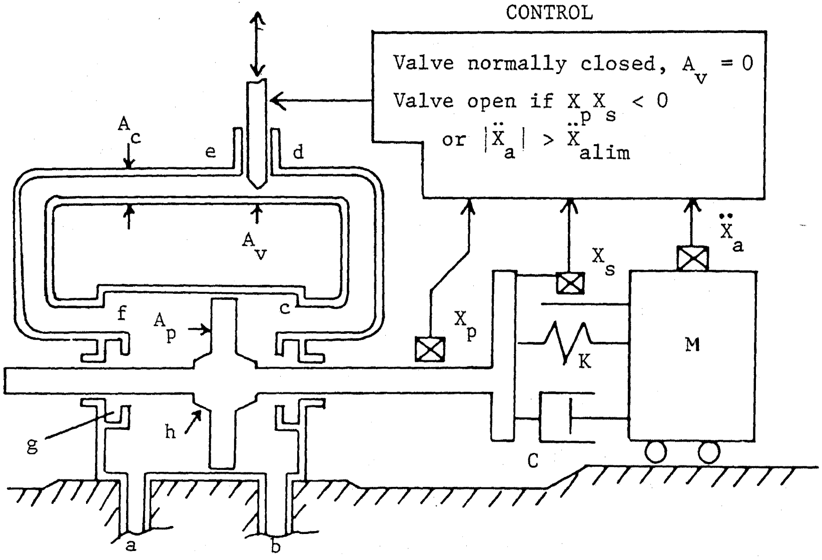

Fig. 2. Semi-active earthquake isolation system

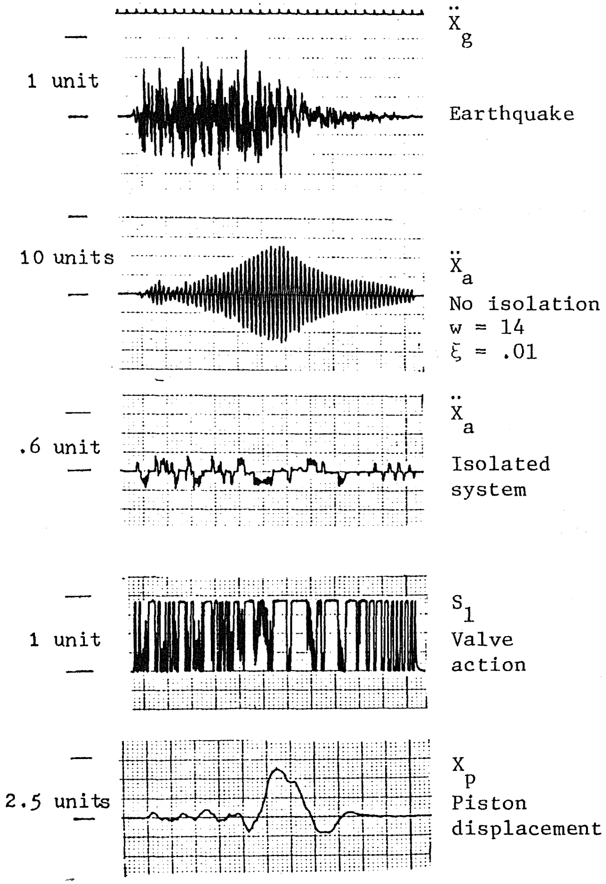

Fig. 3. Simulated response of isolated vs. non isolated system

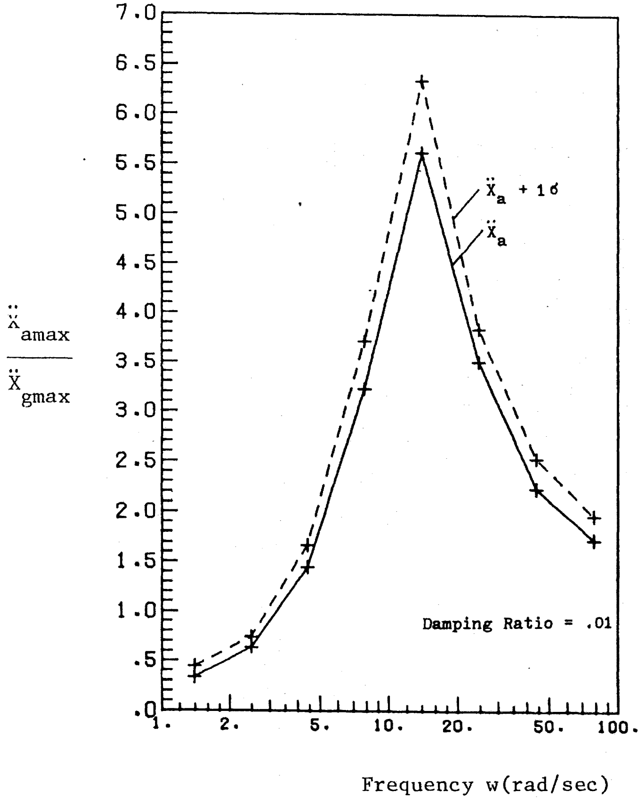

Fig. 4. Peak acceleration response of mass with passive isolation

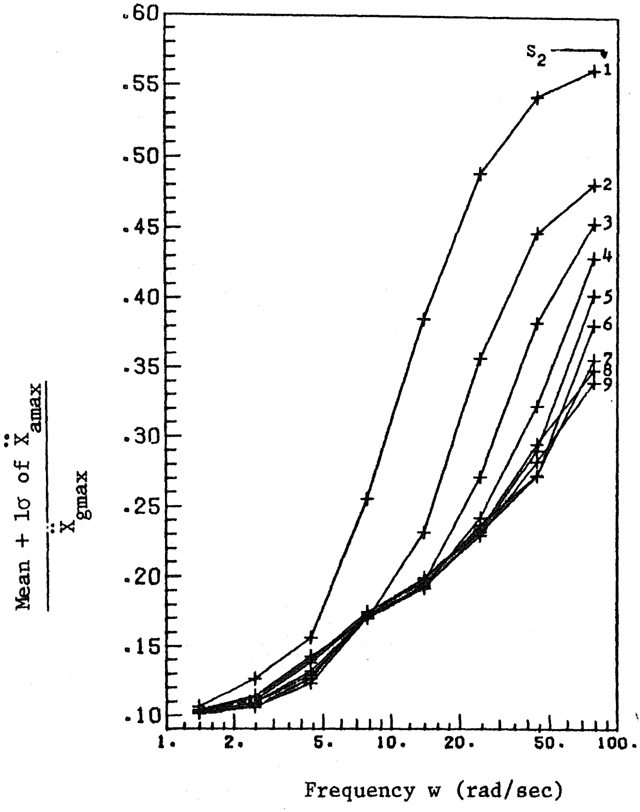

Fig. 5. Peak acceleration response of mass with active system

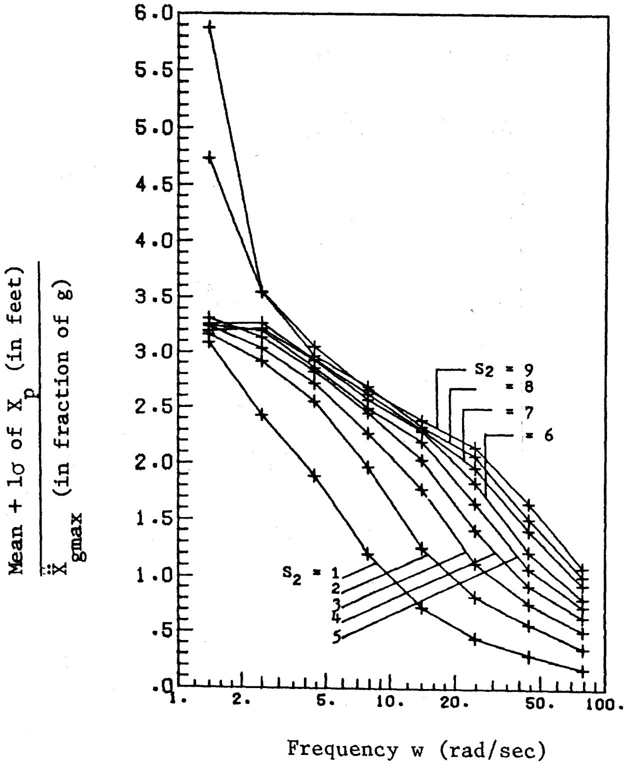

Fig. 6. Peak piston displacement