PASSIVE AND ACTIVE FLUID DAMPERS IN STRUCTURAL APPLICATIONS

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SUMMARY

Analytical and experimental results are presented which demonstrate that the benefits made possible by the use of active control systems may be achieved also by the use of passive and semi-active fluid dampers. However, passive or active fluid dampers offer the advantages of low cost, no or minimal demand for external power, longevity and reliability.

INTRODUCTION

Active control systems which are based on the development of external forces (e.g. developed by actuators or actively moving masses) have been extensively studied. Soong [1] demonstrated that the effect of the active control is to primarily modify the structural properties of stiffness and damping. In fact, successful experimental studies with an active tendon system, [1] and [2], demonstrated that the primary effect of active control was to increase damping of the tested system with only minor or insignificant modification of stiffness.

This observation leads to an important conclusion: that it is possible to achieve structural control comparable to that of active control by the use of passive or semi-active damping devices. Passive damping devices in the form of fluid dampers have been already tested and demonstrated to be very effective in controlling seismic response [3],[4]. Semi-active devices, again in the form of fluid dampers, are described in this paper, and their utility is demonstrated.

Structural control methods involving passive or semi-active fluid dampers have, unlike active force methods, the following advantages:

(a) Low cost. Low cost is primarily achieved by utilizing the motion of the structure itself to generate the required damping forces rather than using external to the structural system means of producing them (e.g. actuators).

(b) Reliability. The reliability of passive fluid dampers is a fact because of their demonstrated good performance over the last twenty years in military applications. Semi-active fluid dampers operate by the same principles as passive fluid dampers. Failure of operation of the active fluid damper results in a change of the active device to a passive one with predetermined damping characteristics.

(c) Power requirements. Passive fluid dampers do not have external power requirements. Rather, semi-active fluid dampers merely operate on electric signals supplied by a battery.

(d) Longevity. Fluid dampers have longevity already demonstrated by several years of continuous use in the harsh environment of military applications.

This paper presents a summary of experimental results which demonstrate the utility of passive fluid dampers in the control of seismic response of buildings and seismically isolated bridges. The results demonstrate that passive fluid dampers produce reductions in seismic response which are comparable to those of active control. Furthermore, this paper presents analytical results on the utility of semi-active fluid dampers. Designs of such dampers are presented.

PASSIVE FLUID DAMPERS

Hydraulic damping devices which utilize fluid flow through orifices have found numerous applications in the shock isolation of military hardware and in the shock and vibration isolation of vehicles. Typical weapons grade shocks have peak free field velocities and accelerations of the order of 4.5 m/sec and 200g, respectively.

One such device has been recently tested for its use as a passive energy dissipating system for buildings and bridges [3],[4]. The construction of this device is shown in Fig. 1. It consists of a stainless steel piston with bronze orifice head and an accumulator. It is filled with silicon oil. The orifice flow is compensated by a passive bi-metallic thermostat that allows operation of the device over a temperature range of -40°C to 70°C. This construction originated within a product used in a classified application on the U.S. Air Force B-2 Stealth Bomber. The performance characteristics of the device are considered as state-of-the-art in hydraulic technology.

The tested fluid dampers utilized an orifice called Fluidic Control Orifice, a design which is capable of delivering damping forces proportional to $\dot{u}^{\alpha}$, where $\dot{u}$=velocity and α=coefficient in the range 0.5 to 1.2. The tested dampers had a coefficient α equal to unity, thus they behaved as linear viscous dampers. This behavior dominated for frequencies of motion below a predetermined cutoff frequency (related to the characteristics of the accumulator valves). Beyond this frequency (set at about 4 Hz), the fluid dampers exhibited strong stiffness in addition to substantial ability to dissipate energy. The existence of the cutoff frequency is desirable, since the lower modes of vibration are only damped while the higher ones are both damped and stiffened so that their contribution is completely suppressed.

Results obtained with this fluid damper in building applications have been presented in Ref. [3], from where a sample is used herein. A 3-story, 28.5kN, moment resisting steel model structure at quarter length scale was tested with and without fluid dampers. The same structure, with only slightly different characteristics, was earlier tested with an active tendon system [1],[2]. Table 1 compares the recorded response of this structure subjected to the 1940 El Centro, component S00E excitation when uncontrolled and when controlled by either an active tendon system or by passive fluid dampers. It is evident in this table that the effect of the active tendon system is to only modify damping, an effect which can be reliably produced by fluid dampers. Actually, the level of damping achieved by the fluid dampers is such that for this particular structure and excitation, the fluid dampers have a clearly superior performance to that of active control.

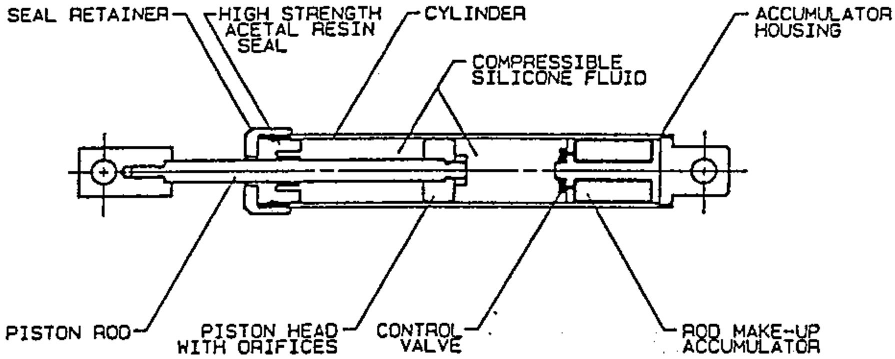

Fig. 1. Construction of passive fluid damper

Equally significant results were recently obtained in bridge applications. The quarter length scale bridge model shown in Fig. 2 was tested with a sliding isolation system as part of the NCEER-Taisei bridge isolation project [4]. The deck (weight $W = 143kN$) was supported by sliding bearings on top of flexible piers. The bearings exhibited friction coefficient of 0.16 at high velocity of sliding. Restoring force was provided by rubber devices placed between the deck and the supporting piers. Period of vibration in the isolated mode was about 1.4 secs in the model scale.

Tests were conducted with actual and simulated motions compatible with bridge design spectra in the U.S. and Japan. Some of the results obtained with motions compatible with the Japanese bridge design spectra for Level 2 earthquake are presented.

In the design of the isolation system an attempt was made to provide effective isolation while maintaining bearing displacements below the limit of 50mm (or 200mm in prototype scale). In the test with the Level 2, ground condition 1 excitation, the rubber devices were stretched to the limit of their fail-safe action, resulting in large isolation and pier shear forces. Tests with motions compatible with the spectra of ground conditions 2 and 3 were not conducted. The results are summarized in Table 2.

Table 1. Comparison of response of tested 3-story model structure

Control Method	System Parameters		Excitation	Floor or Story	Peak Floor Accel. (g)	Peak Inter-story Drift/ Height (%)	Ref.
	f(Hz)	ξ(%)					
Uncontrolled	2.24	1.62	El Centro S00E PGA=0.085g	3	0.322	0.596	1,2
	6.83	0.39		2	0.221	0.874	
	11.53	0.36		1	0.158	0.667	
Active Tendon System	2.28	12.77	El Centro S00E PGA=0.085g	3	0.200	0.405	1,2
	6.94	12.27		2	0.138	0.592	
	11.56	5.45		1	0.139	0.392	
Uncontrolled	2.00	1.74	El Centro S00E PGA=0.157g	3	0.585	1.073	3
	6.60	0.76		2	0.410	1.498	
	12.20	0.34		1	0.389	1.386	
Passive Fluid Dampers Placed at all Stories	2.03	19.40	El Centro S00E PGA=0.152g	3	0.205	0.489	3
	7.64	44.70		2	0.152	0.510	
	16.99	38.04		1	0.127	0.281	
Passive Fluid Dampers Placed at First Story	2.11	17.70	El Centro S00E PGA=0.156g	3	0.282	0.465	3
	7.52	31.85		2	0.221	0.660	
	12.16	11.33		1	0.170	0.540	

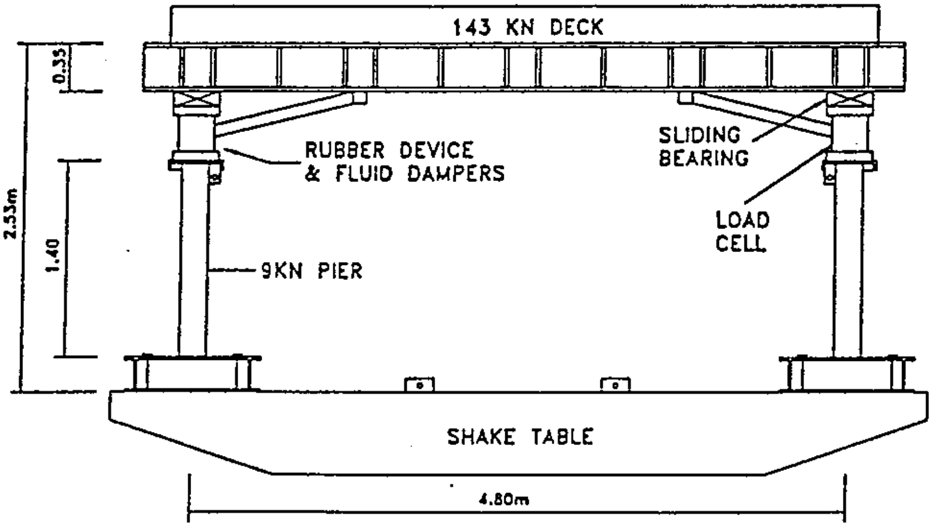

Fig. 2 Model in bridge isolation system testing

Table 2. Summary of Experimental Results of Isolated Bridge (Length Scale = 4)

Isolation System	Excitation	Bearing Displ. (mm)	Base Shear/Weight	Pier Shear/Weight	Pier Displ. (mm)	Case in Fig 3
Rubber Device	Japanese Level 2 G.C. 1	49.3	0.46	0.50	7.2	a
Rubber Device, Fluid Damper	Japanese Level 2 G.C. 1	40.0	0.28	0.33	5.5	b
Rubber Device, Fluid Damper	Japanese Level 2 G.C. 2	38.1	0.31	0.36	5.8	c
Rubber Device, Fluid Damper	Japanese Level 2 G.C. 3	36.9	0.30	0.35	5.6	d

Subsequently, fluid dampers (identical to those used in the building tests) were added in parallel to the rubber restoring force devices. Recorded results for the three types of input motion are listed in Table 2. Forces were reduced to 0.3W, a significant improvement. Evidently, the use of passive fluid dampers caused a marked reduction in the isolation system force and pier shear force and reduced bearing displacement. Fig. 3 shows the recorded response (in terms of only the isolation system hysteresis loop) of the four cases of Table 2.

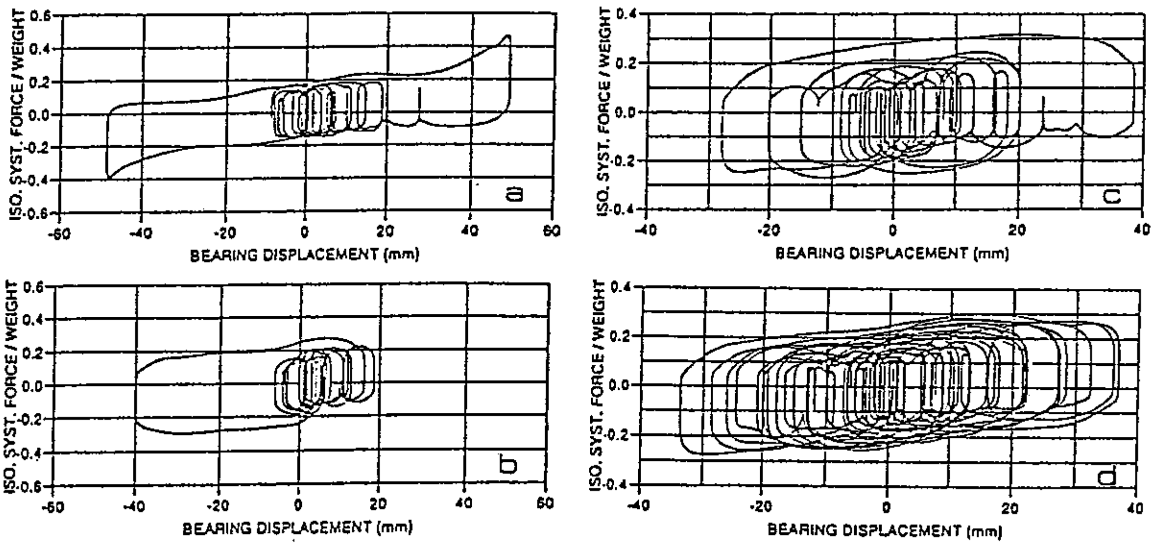

Fig. 3 Recorded response of the bridge isolation system

SEMI-ACTIVE AND ACTIVE FLUID DAMPERS

A state-of-the-art in hydraulic technology fluid damper, as the one depicted in Fig. 1, may be, in principle, easily modified to a semi-active or full-active damper. The concept advanced herein is to direct part of the flow through one or more orifices, which are controlled by valves, while maintaining the primary flow around the piston head.

(a) Simple Two-Stage Fluid Damper

Fig. 4 shows the concept of a simple two-stage fluid damper. Fluid is bypassed through a solenoid valve which is normally closed. Accordingly, the device may operate in a fail-safe manner in which inability to operate the valve results in normal passive operation with maximum damping capacity. Operation of the solenoid valve, which is done by an electrical signal, opens the valve. This allows flow through the secondary orifice, thus increases the available flow area and decreases damping capacity to a minimum. It is a design suitable for bang-bang control. Feng [5] demonstrated the utility of this simple active damper. It should be noted that both orifices could be fitted with the aforementioned passive bi-metallic thermostat for temperature compensation. This is particularly important in bridge applications where the system is exposed to the elements of nature.

(b) Multi-Stage Fluid Damper

A fluid damper capable of producing several levels of controllable damping capacity may be constructed by introducing several solenoid valves rather than the one depicted in Fig. 4. As an example, a five-stage damper requires four solenoid valves.

(c) Fully-Active Fluid Damper

A fluid damper with capability for continuous adjustment of its damping capacity may be produced by using the concept of Fig. 4 with the solenoid valve replaced by a servovalve. Kawashima [6] described one such device.

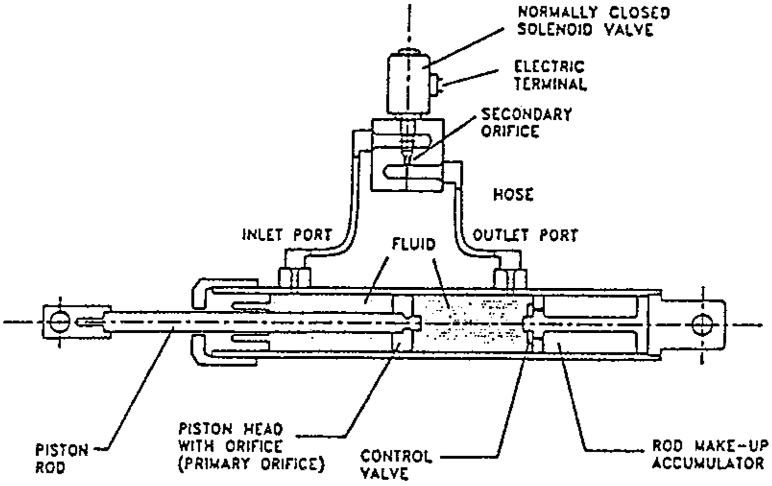

Fig. 4. Construction of two-stage semi-active fluid damper

EXAMPLES OF UTILITY OF SEMI-ACTIVE FLUID DAMPERS

The 3-story structure tested with passive fluid dampers [4] was also tested as a one-story structure by bracing its top upper floors. In this configuration, the structure has weight $W=28.75$ kN, fundamental frequency of 2.0 Hz and corresponding damping ratio (without dampers) of about 0.01. One may note that the frequency of the structure is still the same as that of the 3-story. The one-story structure suffered damage in earlier testing and it was tested with added dampers in that condition. However, it was repaired prior to testing as 3-story structure.

Tests were conducted with two and four passive fluid dampers installed to the one-story structure at an angle $\theta=36°$ between the base and the first floor. The damping ratios were, respectively, changed to 0.28 and 0.57 of critical.

Recorded time histories of interstory drift over height ratio and base shear force-drift loops are shown in Fig. 5 for the 1940 El Centro, component S00E excitation. For comparison, we note that the undamped structure had a peak drift of 1.842% of the story height and peak base shear force of 0.228W when excited with only 1/3 of El Centro [4]. The damped structure has drift ratio of 1.693% and 1.031% and shear force of 0.259 W and 0.301 W in the two cases of damping for a three times stronger earthquake. It should be noted that the addition of four, rather than two dampers, further reduced the drift but increased the base shear force.

The utility of the two-stage damper of Fig. 4 is explored by assuming that the four passive fluid dampers are converted to semi-active ones and used in the structure. The equation of motion of the one-story structure is written as

$$\ddot{u} + 2\xi_u\omega_o\dot{u} + \omega_o^2 u + \frac{P}{m} = -\ddot{u}_g \tag{1}$$

where ω_0 = undamped frequency, ξ_u = damping ratio in the undamped structure, u = relative displacement, $\ddot{u}_g$ = ground acceleration, m = mass and P = force from the fluid dampers. Force P is modeled as

$$P + \lambda\dot{P} = NC_o\cos^2\theta\,\dot{u} \tag{2}$$

where N = number of dampers, C_o = damping constant of one damper at the limit of zero frequency and λ = relaxation time of dampers. The model of Eq. 2 accounts for the stiffening effect of the dampers at large frequencies. Parameters λ and C_0 were experimentally determined to be 0.006 secs and 15.45 N-s/mm, respectively. Eq. 2 may be also written as

$$\frac{P}{m} + \lambda\frac{\dot{P}}{m} = 2\xi_d\omega_o\dot{u} \tag{3}$$

where ξ_d is a damping ratio equal to $NC_o\cos^2\theta/2m\omega_o$.

The design of the two-stage fluid dampers is such that ξ_d is 0.55 when the solenoid valve (see Fig. 4) is closed and is 0.28 when the valve is open. This corresponds to values of C_o equal to 14.45 N-s/mm and 7.88 N-s/mm, respectively. Thus, when the solenoid valve is closed the system behaves as that with four passive dampers, while when the valve is open the system behaves as that with two passive dampers.

First, the analytical model of Eqs. 1 to 3 is used to predict the experimental results with two and four passive dampers for the 1940 El Centro excitation. Fig. 5 demonstrates the good agreement between the two sets of data.

Subsequently, the analysis was repeated with two-stage dampers. The control algorithm was simple and based on the base shear coefficient, V/W, where $V = m(\ddot{u}+\ddot{u}_g)$ and W=weight:

$$\begin{aligned} &\text{Solenoid } \mathit{Valve\ Closed}\ (\xi_d=0.55)\ \mathit{when}\ \frac{V}{W} \le BSCL \\ &\text{Solenoid } \mathit{Valve\ Open}\ (\xi_d=0.28)\ \mathit{when}\ \frac{V}{W} > BSCL \end{aligned} \tag{4}$$

where BSCL is a limit set at 0.20 and 0.25. It should be noted that the control algorithm requires only data collected from accelerometers and it does not require any knowledge of the structural system properties.

The computed responses in the two cases of limit are presented in Fig. 5. The computation was performed in two ways. In the first (termed instantaneous), it was assumed that it is possible to have information on the base shear coefficient and also operate the solenoid valve at any arbitrary time. In the second, it was assumed that information on the base shear coefficient and operation of the valve are possible every 10 msec.

Finally, a last computation was performed with random operation of the solenoid valve, as it would have been the case of malfunction of the solenoid valve. In this case a uniformly distributed random number, RN, over the range 0 to 1 was created at arbitrary times separated by less than 10 msecs intervals. The valve was opened when RN < 0.5 and closed when RN ≥ 0.5. The computed response is also shown in Fig. 5.

The results of Fig. 5 demonstrate the following:

(a) The instantaneously operated two-stage fluid damper systems produce an improvement over the passive systems. The improvement is characterized by reduction of the base shear force coefficient to a value almost equal to the limit BSCL, while drifts are maintained at the level of the passive four damper system.

(b) When the two-stage damper system operates at intervals of 10 msecs or larger, the improvement on the response is still noticeable but not as good as in the instantaneously operated system. In this respect it is worthy of noting that solenoid valves with response time of 1 msec are available, while typical fuel injection cars operate with solenoid valves of about 10 to 20 msecs response time. This indicates that response characteristics equivalent to instantaneous operation are experimentally feasible.

(c) Random operation of the valve does not cause any detrimental effect.

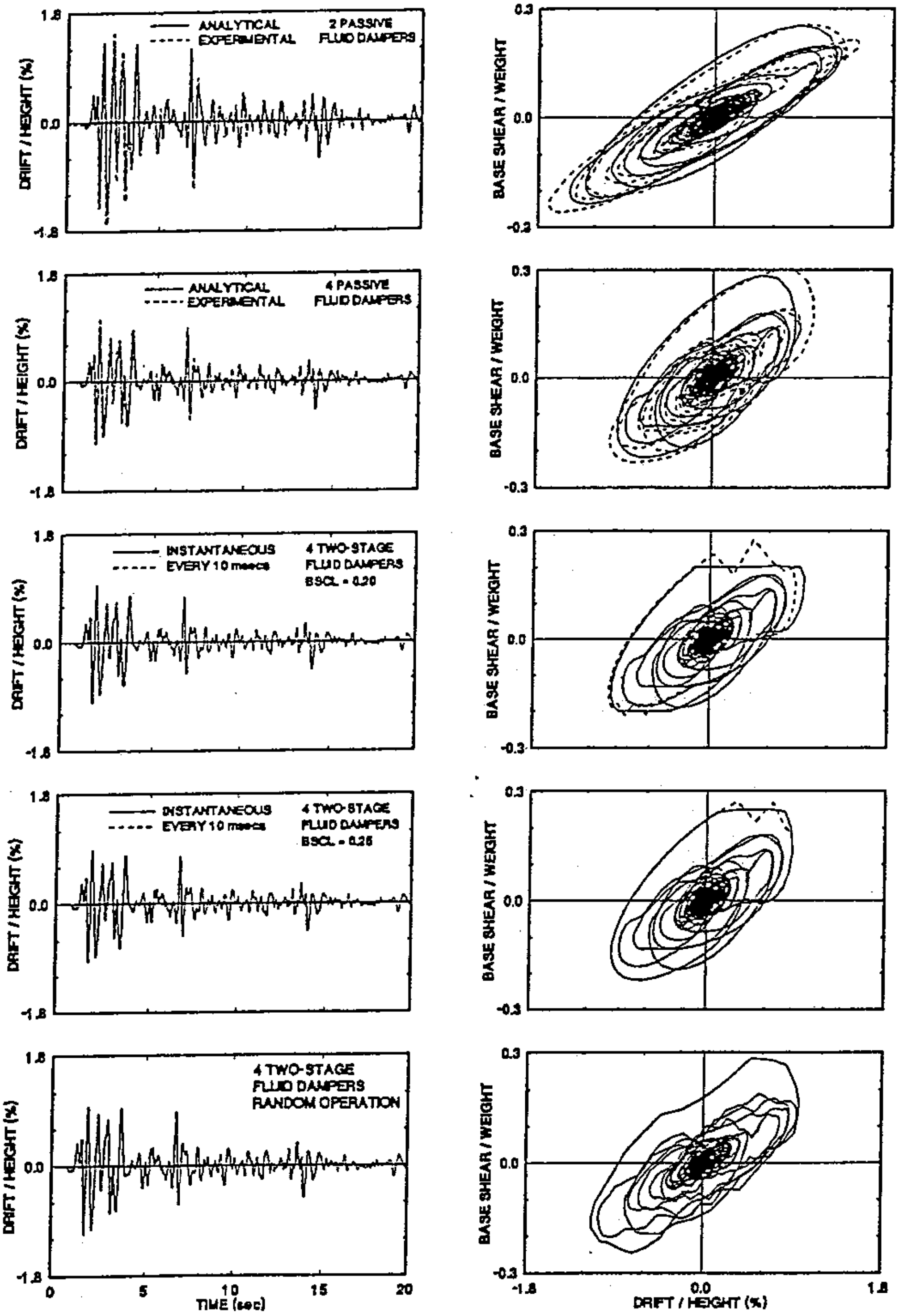

Fig. 5 Response of one-story structure controlled by passive and two-stage fluid dampers

CONCLUSIONS

Passive fluid dampers can achieve reductions in response of structural systems which are equivalent to those achieved by active control. Moreover, fluid dampers are substantially more reliable, have demonstrated longevity, demand no power and cost significantly less than active systems.

Simple semi-active fluid dampers can be easily produced and are capable of further improving the performance of seismically excited structures beyond that achieved by passive dampers. The analytical results presented herein on the semi-active dampers were based on a rather primitive control strategy. It is apparent that better control strategies may be developed.

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