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

Experimental study and analytical prediction of response of spring-viscous damper isolation system

Nicos Makris & M.C.Constantinou
State University of New York, Buffalo, N.Y., USA

ABSTRACT: The coupled lateral-vertical-rocking dynamic response of a spring-viscous damper isolated structure is considered. The force-displacement relation of viscous dampers is described by an experimentally calibrated fractional derivative viscoelasticity model. The validity and accuracy of the model is demonstrated by comparison to shake table test results.

1 INTRODUCTION

Equipment, machines and buildings are typically supported by helical steel springs for vibration isolation. The addition of viscous damping in these isolation systems prevents the occurrence of resonances but amplifies the response to excitation at high frequencies. However, a type of viscous damper consisting of a moving part immersed in highly viscous fluid (Figure 1) has an important property. Its damping coefficient reduces from a high value at low frequencies to about one tenth or less of that value at high frequencies beyond 10 Hz. Accordingly, resonances are prevented without reduction of the system's vibration isolation effectiveness. The combined spring-viscous damper system can, thus, provide both effective vibration and seismic isolation.

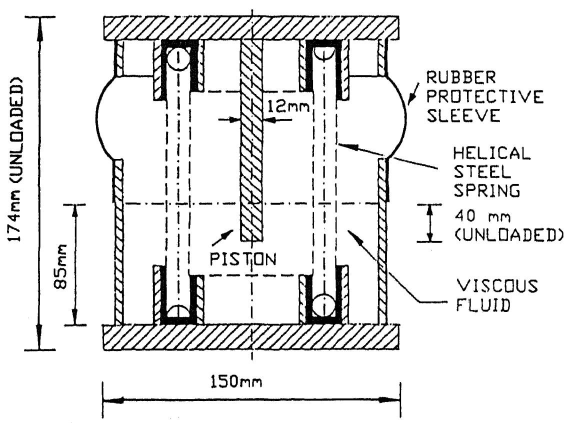


Fig. 1. Construction of Spring-Viscous Damper Unit in Isolated Equipment Tests.

Viscous dampers represent the most complex elements of the spring-viscous damper isolation system. Each damper consists of a moving part immersed in a highly viscous fluid as shown in Figure 1. The moving part (piston) can move in all directions and damping forces develop as a result of shearing action and deformation in the fluid which is contained in a cylindrical pot (GERB 1986).

Viscous dampers exhibit a behavior which is both elastic and viscous with mechanical properties being strongly dependent on frequency. Modeling the behavior of viscous dampers is an increasingly important problem because these devices find a wide range of application in the isolation of buildings, equipment, machines and pipeworks. The authors (Makris and Constantinou 1991) presented a fractional derivative viscoelastic model capable of describing the frequency-dependent properties of viscous dampers.

In this paper an experimental and analytical study of the response of an equipment-cabinet isolated by a spring-viscous damper system is derived. The study concentrates on the seismic response of the system.

2 DESCRIPTION OF ISOLATION SYSTEM

The isolation system consisted of four spring-viscous damper units which were symmetrically placed as shown in Figure 2. The construction of the isolation unit is shown in Figure 1. It consisted of a viscous damper filled with bituminous fluid (density 1125 kg/m^3, dynamic viscosity 11250 Pa-sec at room temperature) and with cylindrical piston of 12 mm diameter. A spring unit of horizontal stiffness K_{xi} = 60 kN/m and vertical stiffness K_{zi} = 46 kN/m was placed inside the damper. This construction results in a compact unit.

A combined spring-viscous damper unit was tested for identification of its mechanical properties. These properties were extracted from the recorded steady-state force-displacement loops in tests of harmonic motion

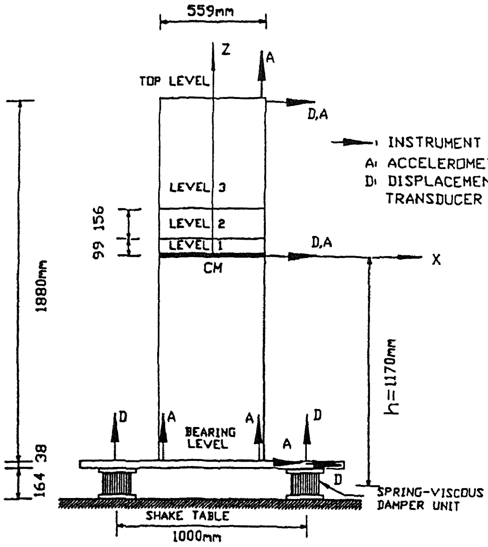


Fig. 2. View of Tested Isolated Equipment and Instrumentation Diagram.

with frequency in the range 0 to 10 Hz and amplitude of either 5 or 10 mm. The properties of storage stiffness (spring stiffness not included) and damping coefficient for vertical motion are shown in Figure 3. The following observations should be made:

1. The damping coefficient has a large value at zero frequency and subsequently drops sharply with increasing frequency.
2. The storage stiffness increases rapidly with frequency, then reduces and finally increases again at higher frequencies. This phenomenon is created by the motion of the spring inside the viscous fluid which at high speeds breaks apart and voids are formed. At higher frequencies a different mechanism causes the stiffness to increase. The increase is caused by the elasticity of the rubber protective sleeve of the damper which is frequency dependent. This complex behavior was not observed in the large damper devices used in building applications where the contribution from the protective sleeve is insignificant (Makris and Constantinou 1991).
3. The properties are amplitude dependent. This dependency was not accounted for in modeling.

The proposed force-displacement relationship for the unit is

$$P(t)+\lambda D^r[P(t)] = C_0 \frac{du(t)}{dt} \qquad (1)$$

in which P(t) = force; u(t) = displacement; λ and C_0 = constants of the model. $D^r[f(t)]$ = fractional derivative of order r of the time-dependent function f(t). A definition of generalized derivative is given through the *Riemann-Liouville integral*

$$I^r f(t) = \frac{1}{\Gamma(r)}\int_a^t f(\xi)(t-\xi)^{r-1}d\xi \quad , \qquad t>a \qquad (2)$$

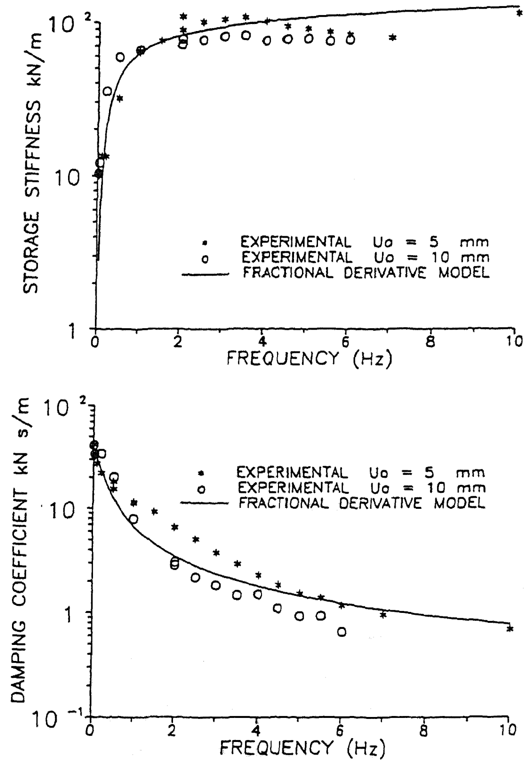


Fig. 3. Mechanical Properties of Viscous Damper and Properties Predicted by Fractional Derivative Model.

where $\Gamma(r)$ is the gamma function. The above integral converges for r>0. However in the case where the function f(t) is n times differentiable, it can be shown that the integral exists for n-r>0 (Oldham and Spanier 1974). In this case the generalized derivative of order r exist and is defined as

$$D^r[f(t)] = \frac{d^r f(t)}{dt^r} = I^{-r} f(t) \quad , \qquad r>0 \qquad (3)$$

In the sequel indices z and x refer to vertical or horizontal directions respectively. Parameters C_{0z} = 42 kNs/m, r_z = 0.8 and λ_z = 0.7 $(sec)^{0.8}$ resulted the mechanical properties shown in Figure 3. The fit of the experimental data on the damping coefficient is seen to be acceptable. The model predicts well the average increase of storage stiffness with increasing frequency but does not capture the observed fluctuations which result from the presence of the spring within the fluid and the contribution of the protective sleeve. The effects of these additional complicated mechanisms are more pronounced at frequencies beyond 10 Hz, where the model overpredicts both the storage stiffness and damping coefficient. Furthermore, it should be noted that the model is valid for large amplitude motion (5 to 10 mm).

For horizontal motion the model parameters were determined to be C_{0x} = 13 kNs/m, r_x = 0.7 and λ_x = 0.15 $(sec)^{0.7}$.

3 EXPERIMENTAL RESULTS

Identification tests of the fixed base cabinet using white noise input gave a fundamental frequency of 10.3 Hz. In its isolated condition, transfer functions obtained in low acceleration amplitude white noise tests and in strong earthquake excitation tests revealed the free vibrational characteristics of the system. They are presented in Table 1. The uncertainty in the third mode frequency was caused by both the motion amplitude dependency of the transfer functions and the high value of damping in that mode.

Table 1. - Free Vibration Characteristics of Isolated Equipment.

	EXPERIMENTAL	ANALYTICAL
f_1 (Hz)	3.5 - 3.6	3.49
f_2 (Hz)	10.6	10.00
f_3 (Hz)	15.6 - 17.8	19.28
ξ_1	0.17 - 0.22	0.17
ξ_2	0.22 (Small Amplitude)	0.15
ξ_3	NOT MEASURED	0.20

It is worthy of noting that the fundamental frequency of the isolated system is 3.5 Hz. This frequency is much higher than the fundamental frequency in elastomeric seismic isolation systems for buildings (typically around 0.5 Hz). A frequency of 0.5 Hz is considerably lower than the predominant frequency of most earthquake excitations, so that isolation is achieved by deflecting the earthquake energy at the expense of large displacements. This is no possible to achieve in equipment isolation systems because of the low frequency content in the floor motion of buildings and the resulting unacceptably large displacements (Makris and Constantinou 1992). Accordingly, the isolation system was designed to be stiff and with high energy absorption capacity at its fundamental frequency.

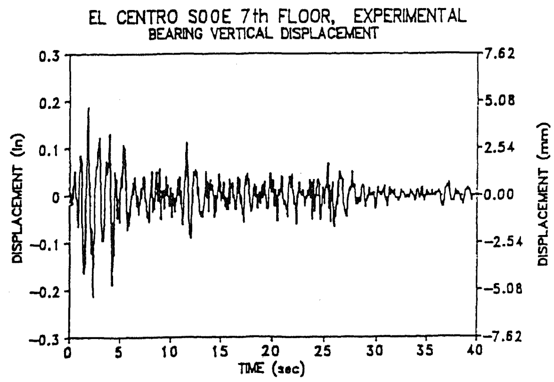
The analytically determined free vibrational characteristics of the isolated cabinet (Makris and Constantinou 1992) are also shown in Table 1. They compare well with the large amplitude experimental values except for the third frequency which is overestimated. The reason for this is the overestimation of the storage stiffness of the damper at frequencies beyond 10 Hz.

The earthquake excitation simulated with the *Buffalo shaking table* consisted of the 1952 Taft (Kern County, CA, Taft Lincoln School tunnel, component N21E and vertical), 1940 El Centro (Imperial Valley, CA, component S00E and vertical) and 1971 Pacoima Dam (San Fernado, CA, component S74W and vertical) records. The Taft and El Centro motions were filtered through an actual 7-story building in an attempt to generate floor motions.

The recorded peak response values of the cabinet under isolated and fixed conditions are presented in Table 2. The location of the instruments is shown in Figure 2. All displacements are measured with respect to the table. The vertical acceleration and displacement values in this table are the maximum recorded among the instruments placed at the two sides of the equipment. The results demonstrate an overall reduction of the acceleration of the isolated equipment in comparison to the fixed (non isolated) equipment, which is more pronounced at the strongest excitations where accelerations reduced by a factor of almost 2. This significant reduction was associated with bearing displacements which did not exceed 10mm.

4 ANALYTICAL PREDICTION OF THE RESPONSE

Structures isolated by helical steel springs and viscous dampers undergo coupled vertical-lateral-rocking response when subjected to ground motion. In this analysis the isolated structure is idealized as a rigid block supported by the spring-viscous damper isolation system. Each viscous damper is described by the constitutive law of equation 1 with different parameters for vertical and horizontal motion. The equations of motion of the rigid block together with the constitutive equations form a system of fractional order differential equations. The formulation and solution of such a system was presented by Makris and Constantinou (1992). The solution was derived by application of Discreet Fourier Transform procedures. Figures 4 and 5 compare experimental and analytical responses in the case of the 7th floor motion for El Centro excitation.



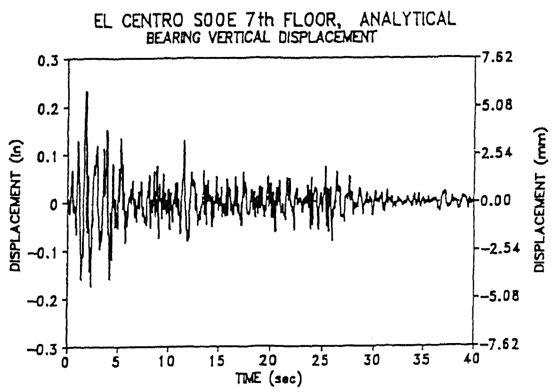


Fig. 4. Comparison of Experimental and Analytical Bearing Vertical Displacement Histories of Isolated Equipment. Input is 7th Floor El Centro Motion.

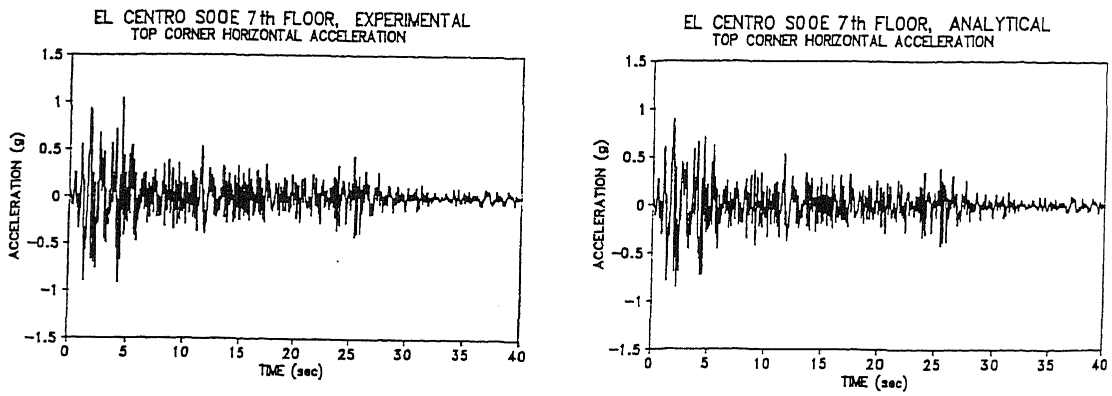


Fig. 5. Comparison of Experimental and Analytical Top Level Horizontal Acceleration Histories of Isolated Equipment. Input is 7th Floor El Centro Motion.

Table 2. - Recorded and Analytically Predicted Peak Response of Isolated Equipment. Value in Parenthesis is for Fixed (Non Isolated) Conditions. Value in Brackets is Analytical.

	TAFT N21E 5TH FLOOR	TAFT N21E 7TH FLOOR	EL CENTRO S00E 5TH FLOOR	EL CENTRO S00E 7TH FLOOR	PACOIMA DAM S74W GROUND
Accel. (g)					
Table Horizontal	0.267 (0.273)	0.471 (0.474)	0.414 (0.417)	0.698 (0.728)	0.838 (0.867)
Bearing Horizontal	0.360 (-)	0.539 (-)	0.483 (-)	0.712 (-)	1.105 (-)
Level 1 Horizontal	0.293 (0.372)	0.513 (0.700)	0.463 (0.529)	0.763 (0.985)	0.961 (1.136)
Top Horizontal	0.394 [0.409] (0.528)	0.836 [0.835] (1.168)	0.605 [0.575] (0.750)	0.985 [0.890] (1.804)	1.635 [1.776] (2.610)
Bearing Vertical	0.031 (-)	0.081 (-)	0.079 (-)	0.234 (-)	0.325 (-)
Top Vertical	0.035 (0.021)	0.100 (0.043)	0.082 (0.042)	0.250 (0.073)	0.342 (0.093)
Displ. (mm)					
Table Horizontal	42.3 (41.3)	53.0 (52.3)	107 (107)	131 (131)	103 (103)
Bearing Horizontal	1.9 [1.8] (-)	2.7 [2.7] (-)	2.7 [2.9] (-)	4.9 [4.9] (-)	6.8 [7.1] (-)
Level 1 Horizontal	6.2 (1.1)	11.0 (1.9)	10.7 (2.4)	20.4 (4.55)	28.0 (4.0)
Top Horizontal	10.3 (2.1)	18.3 (4.7)	17.8 (4.5)	34.0 (8.9)	46.2 (8.7)
Bearing Vertical	2.7 [2.6] (-)	3.8 [4.1] (-)	3.8 [3.5] (-)	5.4 [5.8] (-)	10.0 [9.8] (-)

5 CONCLUSIONS

This paper presents an investigation of the dynamic behavior of structures supported by steel spring and viscous fluid dampers. These dampers exhibit strong viscoelastic behavior which is described by fractional derivative models. The following conclusions were drawn:

1. Spring-viscous damper isolation systems are capable of providing effective vibration and seismic isolation. This property results from the dependency of the damping coefficient of viscous dampers on frequency. At large frequencies damping is low and effective vibration isolation is achieved. At low frequencies damping is high and seismic isolation is achieved.

2 The seismic isolation effect (reduction of acceleration response in comparison to the non-isolated structure response) is not achieved by deflecting the earthquake energy due a significant shift of the fundamental frequency to low values. Rather, it is achieved by absorption of energy in the viscous dampers. This behavior is desirable in the protection of equipment in buildings. Floor response spectra exhibit strong component over a wide range of frequency and thus the use of very flexible isolation systems for equipment is not practical.

3. The seismic isolation effectiveness of stiff spring-viscous damper systems has been demonstrated in shake table tests of an isolated equipment cabinet.

4 The dynamic response of spring-viscous damper isolation systems is more accurately described by systems of fractional differential equations. These equations were shown to simulate with good degree of accuracy the recorded response of the tested isolated cabinet.

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