SEISMIC RESPONSE CONTROL OF 3-D PIPING SYSTEM WITH FLUID VISCOUS DAMPERS

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ABSTRACT

Piping systems of nuclear industry are generally made flexible to take care of normal operating temperature. To maintain the required flexibility, number of supports are made as minimum as possible. This results in low damping in piping system. Due to this property, when piping is subjected to seismic loadings, a large amount of energy is input into them. Therefore, to mitigate the damage and to survive the earthquake loading, it is proposed to use mechanical damping devices, which increases the damping in the piping systems. One of the device called fluid viscous damper has been studied here to mitigate seismic response and vibration control in piping systems. Seismic responses of typical 3-D piping systems equipped with fluid viscous damper are investigated analytically under the four artificial earthquake motions with increasing amplitudes in all the three directions of motion. The study is carried out to find the optimum parameter of fluid viscous damper for the piping system. The analytical results thus obtained with fluid viscous damper are compared with the corresponding piping system without damper to establish the authenticity of the proposed procedure of using viscous dampers. It is observed that there is significant reduction in the seismic response of interest like relative displacements, accelerations and the support reactions for the piping system with fluid viscous damper. In general, fluid viscous damper under particular optimum parameters are very effective and practically implementable for the seismic mitigation, vibration control and seismic requalification of piping system.

Key words: *Fluid viscous damper, seismic mitigation, artificial earthquake motions.*

INTRODUCTION

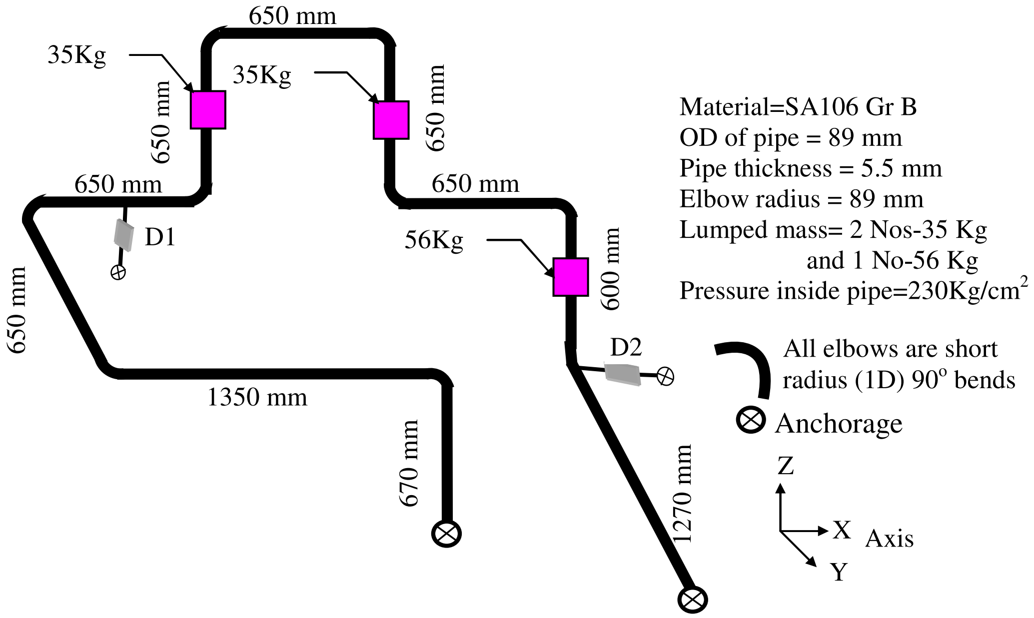
Piping systems, when subjected to seismic loadings, a large amount of energy is input into them. Inherently, piping systems are very low in damping out this input energy, therefore, to mitigate the damage and survive the earthquake it is expected that the dynamic performance of the piping systems could improve by using mechanical damping devices, which increases the damping in the piping systems. In order to dissipate the input seismic energy, fluid viscous dampers with high energy absorption capacity have been applied in the structures to enhance their damping characteristics. Behavior of viscous dampers is unaffected by the frequency contents of the input motion, hence are capable of absorbing energy in broad-banded excitations. Viscous devices operate on the principle of resistance of a viscous fluid to flow through a constrained opening. These devices are widely used as shock and vibration isolation systems for aerospace and military applications. These devices have been adapted for seismic structural applications due to their ability to dissipate large amount of the input earthquake energy by viscous heating. Hence, it will be very interesting to investigate the inclusion of these dampers in piping system.

Mahmoodi [1] initiated the preliminary work and proposal for use of visco-elastic dampers in the year 1972. Tsai [2] presented innovative design, which he claimed was superior to the dampers proposed by Mahmoodi and Keel [3]. Application of these devices to piping systems and equipments was first proposed by Kuneida and Sakurai [4] in the year 1975. Later on, subsequent experimental and analytical work on piping systems controlled using these devices is reported from Kunieda [5] and Chiba and Kobayashi [6]. Recent studies on optimal design of visco-elastic dampers are reported by Shukla and Datta [7] and Park *et al*. [8]. Singh and Moreschi [9] investigated the optimal parameters and location of viscous and VE dampers using genetic algorithm. The studies presented so far mostly covers the experimental investigations and analytical modeling of viscous and solid VE dampers. However, numerical studies on the design parameters of fluid viscous is not much reported for application in piping systems and equipments.

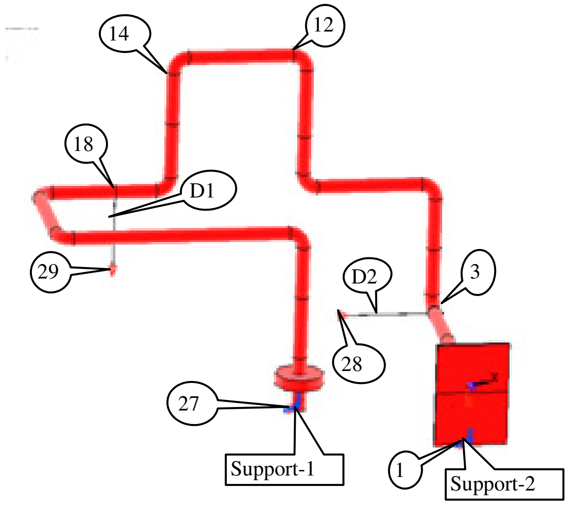
In this study, firstly, the investigation aims at obtaining the design parameters of fluid viscous dampers attached to an industrial piping system. The piping system is attached with three dampers (one in vertical direction and two numbers in horizontal direction) and is subjected to four artificial earthquake motions with increasing amplitudes in all the three directions of motion. The capability of three dampers in reducing the seismic responses of the piping system is then presented by comparing the responses of controlled piping system (obtained using design parameters) and the uncontrolled piping system. The effect of fluid viscous dampers on the modal damping ratios of the piping system is also presented.

PIPING SYSTEM AND MODELING OF PIPING SYSTEM WITH VISCOUS DAMPERS

Figure 1 (a) and 1 (b) shows a schematic diagram and FE model of the industrial piping system with and without fluid viscous dampers considered for the study. In the finite element modal, the two ends which are rigidly fixed are considered as restrained in all degree-of-freedom. The damper locations are highlighted as D1 and D2 effective in Z- and X-direction of the piping system, respectively. In addition to the mass of piping system, the externally lumped masses are assumed to be effective in the three translational degrees-of-freedom.



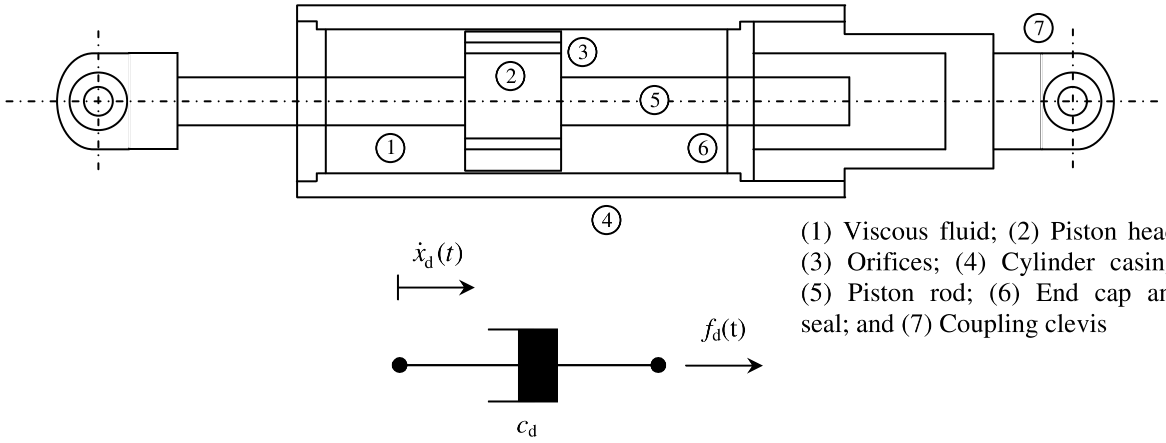
(a) Schematic of a piping system with dampers



(b) FE model of piping system with dampers

Figure 1. Schematic diagram and FE model showing the arrangement of damper in piping system

Figure 2 shows a schematic diagram of a typical viscous damper proposed by Constantinou and Symans [10] and Symans and Constantinou [21].



(1) Viscous fluid; (2) Piston head; (3) Orifices; (4) Cylinder casing; (5) Piston rod; (6) End cap and seal; and (7) Coupling clevis

Figure 2 Schematic diagram viscous damper (Constantinou *et al.*, 1998)

The equations of motion of a piping system equipped with fluid viscous damper, under the ground motion are expressed in the following matrix form:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=-[M]\{r\}\ddot{u}_g \tag{1}$$

$$\{u\} = \{x_1, y_1, z_1, \theta_{x1}, \theta_{y1}, \theta_{z1}, x_2, y_2, z_2, \theta_{x2}, \theta_{y2}, \theta_{z2}, \ldots\ldots., x_N, y_N, z_N, \theta_{xN}, \theta_{yN}, \theta_{zN}\}^{\mathrm{T}} \tag{2}$$

where $[M]$, $[C]$ and $[K]$ represents the mass, damping and stiffness matrix, respectively of the piping system with fluid viscous damper of order $6N \times 6N$, where N is the number of nodes; $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ represent acceleration, velocity and displacement vectors, respectively; $\{r\}$ is the influence coefficient vector; $\ddot{u}_g$ is the earthquake ground acceleration; and x_i, y_i and z_i are the displacements of the i^{th} node in the piping system in X-, Y- and Z-directions, respectively. A lumped mass matrix is obtained by ignoring the masses in the rotational degrees-of-freedom and it has a diagonal form. The stiffness matrix of the piping system is constructed separately and then static condensation is carried out to eliminate the rotational degree-of-freedom. The damping matrix of the overall system (i.e. piping system with dampers) is obtained by adding the inherent structural damping matrix $[C_s]$ and the damping contribution from the dampers and is expressed by

$$[C] = \sum_{p=1}^{n_d} [C_s] + [u_f^p] c_d^p \tag{3}$$

where $[C_s]$ is the damping matrix of the piping system alone; $[u_f^p]$ is the location matrix of the p^{th} damper and c_d^p is the damping coefficient of the p^{th} damper.

With the first two natural frequencies of the piping system known, and the damping ratio obtained from the test model, the damping matrix is obtained by using Rayleigh's method. The damping ratio of piping system considered in analysis as obtained from experimental data is 1.2 %. The time history analysis of piping system without and with fluid viscous damper is performed with input excitation of artificial earthquake motions with increasing amplitudes and designated as TH10, TH20, TH30 and TH40. The specific components of these artificial earthquake motions are indicated in Table 1.

Table 1. Peak ground acceleration of various artificial earthquake motions

Artificial earthquake motions	Peak ground acceleration (m/sec^2)		
	x- component	*y*- component	*z*-component
TH10	2.38	2.15	1.88
TH20	4.85	4.15	3.22
TH30	7.17	6.31	4.91
TH40	10.01	8.65	6.25

The force-deformation behavior of the viscous damper is considered same as the conventional velocity dependent purely viscous dashpot model as shown in Figure 2. The force in the damper, $f_d(t)$ at any instant of time, t is expressed by

$$f_{\mathrm{d}}(t) = c_{\mathrm{d}}\dot{x}_{\mathrm{d}}(t) \tag{4}$$

where c_{d} is the damping coefficient of the damper; and $\dot{x}_{\mathrm{d}}(t)$ is the velocity in the damper at any time, t.

From equation (4), it is observed that the only parameter that affects the performance of a viscous damper is its damping coefficient. Firstly, it is assumed that the dampers are having constant damping coefficient (i.e. $c_{\mathrm{d}} = c_{\mathrm{d1}}, c_{\mathrm{d2}}$). Then, to obtain the design parameters of the viscous dampers, the seismic responses of the controlled piping system are noted for different values of damping ratios in the dampers in the practical range of the ratio c_{d}/c_p= 0 to 20, where c_p is the first mode damping coefficient of the uncontrolled piping system expressed as

$$c_p = 2\xi_p m_1 \omega_{\mathrm{p1}} \tag{5}$$

where ξ_p is the damping ratio; ω_{p1} is the fundamental natural frequency; and m_1 is the corresponding modal mass of the piping system.

NUMERICAL STUDY ON FLUID VISCOUS DAMPER

The response quantities of interest for the piping system under consideration are the relative displacements (x_p, y_p or z_p), accelerations ($\ddot{x}_p$, $\ddot{y}_p$ or $\ddot{z}_{\mathrm{p}}$) of the piping system at the damper-piping connections and the support reactions (R_x, R_y or R_z). The *x, y* and z in the response quantities refer to the responses in the X, Y and Z-directions of the piping system, respectively. The responses are noted for, (i) uncontrolled system (i.e. piping system without dampers), (ii) controlled system with constant damping (i.e. piping system with constant damping ratios in all dampers). The relative displacements of the piping system at the damper locations are crucial from design point of view of both, the dampers and the piping system. Whereas, the accelerations of the piping system and the reactions at the support are directly proportional to the forces exerted on the piping system.

In this study, the design parameters of the fluid viscous dampers are obtained numerically. The method consists of monitoring the seismic responses of the piping system by varying the damper parameters in the range of their practical values.

It is observed from Figure 3 that the displacement responses of the piping system are reduced for increase in the damping ratio of the damper in a practical range of 0 to 20 under all artificial earthquake motions. Similar trend is also observed in case of acceleration and support reaction in piping system. It is observed that for initial values of c_{d}/c_p (i.e. up to 5), the rate of the response reduction is significant with lower rate of reduction for further increase in the value of c_{d}/c_p. This is due to the fact that the piping system has low inherent damping and addition of dampers increases the modal damping ratios of the piping system which damps the contribution of responses in individual modes.

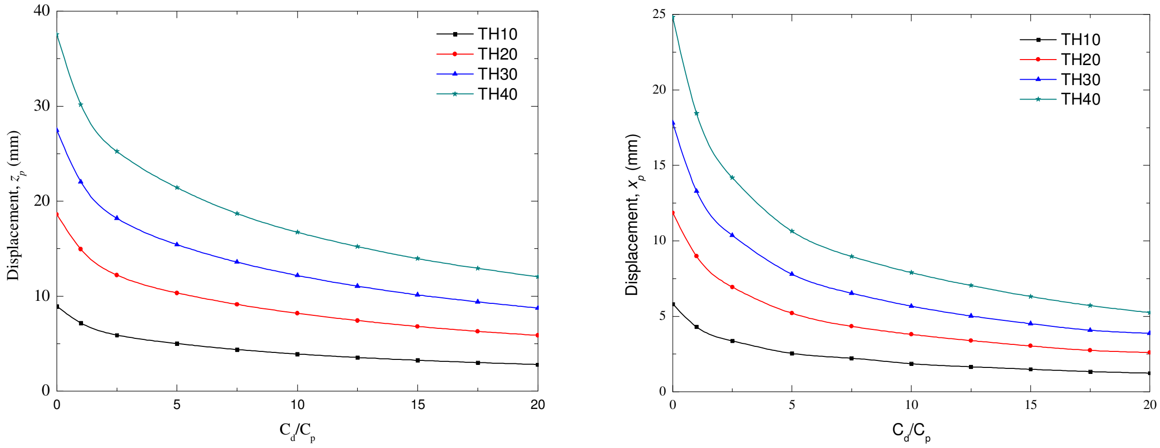


Figure 3 Variation of displacement against C_d/C_p at D1 and D2 of piping system with both vertical and horizontal viscous damper under different time histories

Table 2 shows comparison of the natural frequencies and modal damping ratios for the first 10 modes of the uncontrolled and controlled piping system. It is noted from Table 2 that the inherent damping is in the piping system in the fundamental mode, which was initially 1.2% is increased to 8.98%. The fundamental natural frequencies of the piping system obtained by the uncontrolled and controlled are found to be same.

Table 2 Natural frequency and modal damping ratios of the piping systems

Mode	Uncontrolled			Effective mass participation (Uncontrolled)			Controlled with viscous dampers		
	f	ω	ξ_p	X-direction	Y-direction	Z-direction	f	ω	ξ_p
	(Hz)	(rad/s)	(%)	%age	%age	%age	(Hz)	(rad/s)	(%)
1	4.03	25.32	1.2	9.58	17.79	42.82	4.03	25.32	8.98
2	4.54	28.56	1.2	32.24	34.41	0.42	4.54	28.56	4.63
3	7.73	48.59	1.2	5.24	1.34	0.19	7.73	48.59	4.99
4	8.96	56.32	1.2	27.58	11.61	35.35	8.96	56.32	4.24
5	12.69	79.77	1.2	6.91	0.00	8.29	12.69	79.77	3.33
6	18.07	113.52	1.2	3.78	0.18	0.05	18.07	113.52	2.75
7	21.77	136.78	1.2	0.62	3.05	0.05	21.77	136.78	2.33
8	31.14	195.71	1.2	1.59	0.14	0.00	31.14	195.71	1.29
9	34.76	218.43	1.2	0.84	8.46	1.45	34.76	218.43	1.69
10	39.96	251.08	1.2	6.29	2.24	0.00	39.96	251.08	1.21

The responses of the piping system are then obtained using the constant damping values and are shown in Tables 3 for piping system with viscous dampers for artificial earthquake motions with increasing amplitudes. The displacement of the uncontrolled piping system in Z-direction is 37.68 mm, which is reduced to 18.89 mm at the damper location D1 and 13.04 mm, which is reduce to 5.21 mm at damper location D2 under the time history, TH20. It is evident from the Table 3 that there is a significant reduction in the displacements, accelerations and support reactions for the piping system with viscous dampers. This implies that viscous dampers are effective in reducing the seismic response of the piping system.

Table 3 Peak response quantities of piping system with fluid viscous damper under table accelerations

Time history	Direction	Uncontrolled at D1			Uncontrolled at D2			Controlled (Constant damping, $c_d/c_p = 5$) at D1			Controlled (Constant damping, $c_d/c_p = 5$) at D2		
		x_p, y_p or z_p	$\ddot{x}_p$, $\ddot{y}_p$ or $\ddot{z}_p$	R_x, R_y or R_z	x_p, y_p or z_p	$\ddot{x}_p$, $\ddot{y}_p$ or $\ddot{z}_p$	R_x, R_y or R_z	x_p, y_p or z_p	$\ddot{x}_p$, $\ddot{y}_p$ or $\ddot{z}_p$	R_x, R_y or R_z	x_p, y_p or z_p	$\ddot{x}_p$, $\ddot{y}_p$ or $\ddot{z}_p$	R_x, R_y or R_z
		(mm)	m/sec^2	(kN)	(mm)	m/sec^2	(kN)	(mm)	m/sec^2	(kN)	(mm)	m/sec^2	(kN)
TH10	X	9.76	12.28	1.01	4.27	7.66	1.49	6.409	4.964	0.752	3.648	4.823	0.908
	Y	15.51	16.43	1.67	0.0046	0.86	1.04	5.903	6.007	0.586	0.066	0.0963	0.462
	Z	18.17	14.13	1.35	6.37	8.35	1.44	9.169	7.267	0.779	2.535	2.896	0.436
TH20	X	20.23	30.62	2.03	8.86	16.01	3.10	13.152	10.54	1.457	7.347	9.112	1.821
	Y	31.97	32.28	3.47	0.0096	1.86	2.21	12.270	13.01	1.212	0.137	0.1924	0.955
	Z	37.68	29.64	2.76	13.04	16.54	2.97	18.899	14.99	1.606	5.207	6.143	0.867
TH30	X	30.19	40.40	2.97	13.39	23.43	4.69	19.601	15.27	2.174	10.943	13.49	2.707
	Y	48.03	47.12	5.22	0.014	2.62	3.36	18.181	19.52	1.802	0.202	0.2643	1.426
	Z	56.15	44.81	4.13	19.59	24.27	4.45	28.368	22.4	2.411	7.798	8.886	1.286
TH40	X	42.31	54.84	4.11	19.83	32.74	6.41	27.231	20.85	30.86	15.445	19.37	3.834
	Y	66.17	66.21	7.16	0.019	3.84	4.47	25.169	27.54	2.511	0.277	3.688	1.878
	Z	72.06	59.81	5.66	27.03	32.28	6.14	39.173	30.97	3.313	10.644	11.69	1.764

Figure 11 shows the force-displacement loops of the viscous dampers (at damper location D1 and D2) for the controlled piping system under TH20. It is observed from the loops that good amount of energy is absorbed by the dampers under TH20 which is further confirmed from the Table 2.

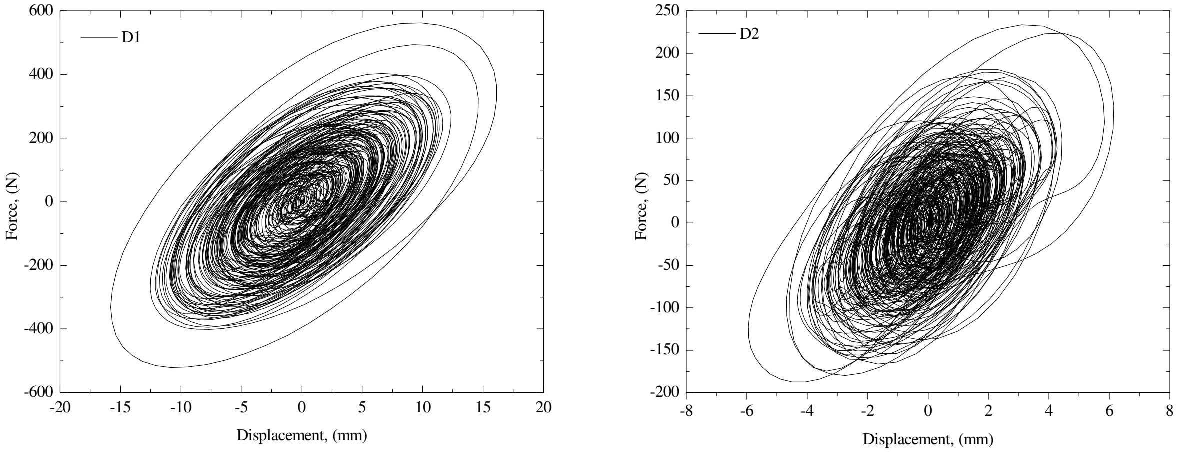


Figure 3 Variation of Force-displacement at D1 and D2 of piping system with both vertical and horizontal viscous damper under time history TH20.

CONCLUSIONS

A numerical study is presented in this paper that investigates the performance of fluid viscous devices for piping system in industrial installations under the seismic excitation. The seismic responses of piping system are studied under important parametric variation of the damper properties under artificial earthquake motions with increasing amplitudes to obtain the optimum properties and design parameters of the damper. Also, the suitability of fluid viscous devices for seismic response reduction of the piping system is studied under artificial earthquake motions with increasing amplitudes. The role of the hysteretic energy dissipated by fluid viscous devices is also studied. The effect of the damper properties on the natural frequency of the piping system is also investigated. Based on the trends of the results, the following conclusions are drawn.

1) Numerical studies show that, viscous damper is very effective in reducing the seismic response of piping system. Hence, the problem of earthquake hazard mitigation, vibration control and seismic requalification of the piping system in industrial installations and utilities like nuclear power plants can be conveniently solved by use of the fluid viscous damper.
2) There exist design parameters of the fluid viscous damper, which when adopted for designing the devices attached to the piping system produces minimum responses of the piping system under given seismic excitation.
3) Natural frequencies of the piping system remain same with viscous damper.
4) Inclusion of fluid viscous dampers in the piping system significantly increases the modal damping of the piping system.

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