Seismic Response of Piping System with Passive and Semi-active Supplemental Devices under Tri-directional Seismic Excitation

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Abstract

In this article, passive and semi-active supplemental devices have been studied to mitigate seismic response and vibration control of piping system used in the process industries, fossil and fissile fuel power plant. A study is conducted on the performance of passive and semi-active supplemental devices due to variation in parameters of devices and or with different control algorithms of the damper and subsequently optimum parameter of devices are obtained. The effectiveness of these devices in terms of reduction in the responses of the piping system is investigated by comparing uncontrolled responses under four different artificial earthquake motions with increasing amplitudes. The results demonstrate that these devices under particular optimum parameters are very effective and practically implementable for the seismic response mitigation, vibration control and seismic requalification of piping systems.

1. Introduction

Piping systems considered as the lifeline of industrial units such as process industries, fossil and fissile fuel power plant. Piping systems are normally installed on those structures in which acceleration at the location of piping support is higher than the ground acceleration. Seismic loads generated in addition to normal load on piping systems due to earthquakes can cause excessive vibrations, which can lead to high stresses resulting in damage or complete failure. Presently, piping systems and mountings are generally supported by seismic supports called snubbers. Moreover, snubbers are associated with operational problems like oil leakage, inadvertent locking-up, undesirable load on piping system due to malfunctioning of snubber and need frequent attention (Olson and Tang, 1988; Jonczyk and Gruner, 1991). At the same time, different structural control methods like passive, active, semi-active and hybrid control devices also known as supplemental devices have been successfully implemented in vibrating systems to reduce structural response due to earthquake and wind loadings (Housner et al., 1997). These devices can replace the snubbers. However, simplified finite element analysis and systematic design procedures for optimal sizing and placement of these protective devices in 3-D piping system subjected to tri-directional seismic excitation are needed and same is not investigated so far.

From the literature review, the X-plate damper(XPD), fluid viscous damper, visco-elastic damper, tuned mass damper (TMD) and multiple tuned mass dampers (MTMDs) as passive devices and MR
damper, variable friction damper and variable stiffness damper as the semi-active devices are proposed to use as supplemental devices to mitigate the seismic response of the piping systems. Four different artificial earthquake motions with increasing amplitudes are proposed to apply at the support of the piping systems. These devices can also be used to upgrade and retrofit existing industrial and nuclear power plant facilities without much hassle.

The main objective of the present study is to develop:
- Optimum design parameter of the piping system equipped with various supplemental devices;
- Optimum parameter of control algorithms for semi-active dampers;
- To investigate the hysteretic energy dissipation behaviour of the various supplemental devices;
- To investigate numerically the feasibility and efficiency of supplemental devices in comparison to uncontrolled piping system;
- Integrated computer program of the complex 3-D piping systems equipped with supplemental devices.

2. **Modelling of Piping System with Damper**

Initially tests were conducted on 3-D piping system without and with XPD under four different artificial earthquake motions with increasing amplitude (refer Table 1) as shown in Fig. 1. Numerical investigations are then carried out for same piping system without and with different passive and semi-active supplemental devices and schematic of piping system with supplemental devices as shown in Fig. 2. Analysis is carried out using a computer code developed, in which straight element in the piping system are modeled as 3-D beam and elbows as 3-D curved beams whose moment of inertia is modified as per ASME codes to account for flexibility and having six degrees-of-freedom at each node. The mass of each member is assumed to be

<table>
<thead>
<tr>
<th>Artificial earthquake motions</th>
<th>Peak ground acceleration (m/sec²)</th>
<th>Duration of earthquake sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x$-component</td>
<td>$y$-component</td>
</tr>
<tr>
<td>TH10</td>
<td>2.38</td>
<td>2.15</td>
</tr>
<tr>
<td>TH20</td>
<td>4.85</td>
<td>4.15</td>
</tr>
<tr>
<td>TH30</td>
<td>7.17</td>
<td>6.31</td>
</tr>
<tr>
<td>TH40</td>
<td>10.01</td>
<td>8.65</td>
</tr>
</tbody>
</table>
distributed between its two nodes as a point mass. In addition to the mass of the piping system, the externally lumped masses are assumed to be effective in the three translational degrees-of-freedom. The dampers attached to the piping system in various combinations during analysis are: vertical, horizontal and both vertical and horizontal. Responses are obtained using Newmark’s step-by-step time-integration technique. The responses evaluated are displacements, accelerations and support reactions/base shears of piping system. Seismic energy dissipation in the piping system governed by the hysteretic characteristics of damper is also evaluated.

3. Governing Equations of Motion

The equations of motion of the piping system attached with supplemental devices, and subjected to earthquake motion, are expressed in the following matrix form:

\[
\{M\} \{\ddot{u}\} + \{C\} \{\dot{u}\} + \{K\} \{u\} + \{\Gamma\} \{F\} = -\{M\} \{\ddot{\Lambda}\} \dot{\ddot{u}}_g \quad (1)
\]

\[
\{u\} = \{x_1, y_1, z_1, \theta_{x1}, \theta_{y1}, \theta_{z1}, x_2, y_2, z_2, \theta_{x2}, \theta_{y2}, ..., x_N, y_N, z_N\}^T \quad (2)
\]

\[
\ddot{u}_g = \{\ddot{x}_g, \ddot{y}_g, \ddot{z}_g\}^T \quad (3)
\]

where \([M], \{C\} and \{K\}\) represents the mass, damping and stiffness matrix, respectively; \(\{\ddot{u}\}, \{\dot{u}\} and \{u\}\) represent acceleration, velocity and displacement vectors, respectively; \(\{\Gamma\}\) is the location matrix for the restoring force of damper; \(\{F\}\) is the vector containing the restoring force of damper; \(\{\Lambda\}\) is the influence coefficient vector; \(\ddot{\Lambda}\) is the vector of earthquake ground accelerations; \(\ddot{x}_g, \ddot{y}_g\) and \(\ddot{z}_g\) are the earthquake acceleration along X-, Y- and Z-directions, respectively and \(x_i, y_i, z_i\) are the displacements and \(\theta_{xi}, \theta_{yi}, \theta_{zi}\) are the rotations of the \(i^{th}\) node in the piping system in X-, Y- and Z-directions, respectively.

4. Numerical Study of Piping System with passive devices

Free vibration characteristics up to four modes with different location of XPD and without XPD in the piping system are listed in Table 2. The analytical and experimental results of XPDs are in very close agreement. It is observed that there is significant reduction in responses such as displacement, acceleration and support reaction in the range of 47 to 67%, 48 to 53% and 48 to 63%, respectively for the piping system with XPDs in Z-direction at D1. The energy dissipated in the hysteresis loops increases as the base acceleration increases from TH10 to TH40. The study on the effect of damper parameters (i.e. height, width and thickness of the XPD) is also investigated under the earthquake motions to find the optimum design of XPDs.

The optimum design parameters of fluid viscous and visco-elastic (VE) dampers are obtained for the same piping system. It is observed that there is significant reduction in responses such as displacement, acceleration and support reaction in the range of 45 to 50%, 48 to 50% and 25 to 39%, respectively for the piping system with fluid viscous dampers in Z-direction at D1. The displacement, acceleration and support reaction is reduce in the range of 53 to 57%, 51 to 52% and 38 to 40%, respectively for the piping system with VE dampers in Z-direction at D1. The inherent modal damping in the piping system in the fundamental mode, which was initially 1.2%, is increased to 8.98% and 6.87% in the piping system with fluid viscous dampers and VE dampers, respectively. Response reduction in VE damper is slightly better than viscous damper, this is because of the additional stiffness property in the VE damper. It is observed that there exist design parameters or optimum parameters of TMD and MTMD system for which minimum response of the piping system is obtained. The design parameters of the TMD system (Jangid, 1997) are obtained for seven values of damping ratios of the main system.
Table 2: Free vibration characteristics of piping system with and without XPDs.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Without XPD</th>
<th>Both vertical and horizontal XPDs</th>
<th>Horizontal XPD</th>
<th>Vertical XPD</th>
<th>Effective mass participation without XPD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency, Hz</td>
<td>Frequency, Hz</td>
<td>Frequency, Hz</td>
<td>Frequency, Hz</td>
<td>X-dir, (%)</td>
</tr>
<tr>
<td>1</td>
<td>4.03</td>
<td>4.06</td>
<td>4.51</td>
<td>4.25</td>
<td>4.03</td>
</tr>
<tr>
<td>2</td>
<td>4.54</td>
<td>4.45</td>
<td>6.05</td>
<td>5.75</td>
<td>4.71</td>
</tr>
<tr>
<td>3</td>
<td>7.73 *</td>
<td>8.60 *</td>
<td>7.93 *</td>
<td>8.60</td>
<td>8.75</td>
</tr>
</tbody>
</table>

Fig. 3: Force-displacement variations at D1 for the piping system with both vertical and horizontal passive devices under TH20.

Fig. 4: Variation of piping responses without and with passive devices subjected to earthquake motions.
(i.e. $\xi_S = 0, 0.01, 0.02, 0.03, 0.05, 0.075$ and $0.1$) for different mass ratios in range of $0.005$ to $0.1$ at an interval of $0.005$. One TMD is designed for damping the first mode of the piping system, which has maximum mass participation. Similarly, number of TMDs in MTMD as 2, 4 & 7 and are designed for reducing the responses in the piping system. It is observed that the inherent modal damping in the piping system in the fundamental mode, which was initially $1.2\%$, is increased upto $6.14\%$.

It is observed from the Fig. 3 that good amount of energy is dissipated by the dampers under all the earthquake motions. It is also observed from Fig.4 that XPD, viscous damper and VE damper are very effective in reducing the seismic response of the piping system.

5. Modeling, control law and numerical study of piping system with Semi-active devices

Semi-active supplemental devices investigated are MR damper, variable friction damper and variable stiffness damper. Semi-active control systems are highly non-linear. One of the main challenges in semi-active control is to develop an appropriate control algorithm. Also, modeling of the control devices is essential for adequate prediction of the behavior of the piping system. The schematic of the piping system with semi-active supplemental devices and the mathematical models of semi-active dampers are shown in Figs.5 and 6, respectively.

Fig. 5: Schematic diagram of piping system with semi active dampers and control feedback system

Fig. 6: Mathematical model of semi-active dampers
Here two versatile and effective control algorithms are selected in the current study and these are; the Bang-bang controller and the Lyapunov controller. The governing equation of the force predicted \(f_d\) by this model is
\[
f_d = c_i \dot{y} + k_a (x_d - x_0)
\]
(4)

where \(c_i\) is viscous damping at lower velocity in the model to produce the roll-off; \(k_a\) is the accumulator stiffness; \(x_0\) is the initial displacement of spring; \(x_d\) is the velocity across the damper. The response of the MR damper is depends on the local motion of the piping system and also on the maximum input command voltage to the current driver. Hence it is important to know the optimum input command voltage, so that resulting MR damper force in a piping system causes optimum reduction in the piping responses. Praveen et al., 2012 studied the response of piping system with MR damper under tri-directional seismic excitation. To obtain the optimum input command voltage a parametric study is made in the range 0 to 2.25V, keeping all other parameters of the MR damper constant. It is observed that, the command voltage plays an important role in the response of the piping system. It is observed that there is significant reduction in responses such as displacement, acceleration and base shear in the range of 69 to 88%, 57 to 73% and 39 to 45%, respectively for the piping system with MR dampers in Z-direction at D1 under the different earthquake motions.

In semi-active variable friction damper (SAVFD), predictive control algorithm (Lu, 2004) with direct output feedback concept is considered. In predictive control algorithm, the critical friction force is dependent on the optimal gain multiplier. Thus, the control force vector when all the dampers are brought into slip state is given by
\[
F(t) = \alpha (G_z F(t - 1) + G_u F(t - 1) + G_u \dot{u}_i(t - 1))
\]
(5)

The factor \(\alpha\) is a ratio of damper force to critical friction force and also \(\alpha\) is treated as gain multiplier. The matrices \(G_z, G_u\) and \(G_w\) are the control gains. A parametric study is made by variation of gain multiplier in the range 0 to 0.99. It is observed that there are significant reduction in responses such as displacement, acceleration and base shear in the range of 93.5 to 94%, 89.3 to 90.4% and 61.4 to 66.5%, respectively for the piping system with SAVFD in Z-direction at D1 under the different earthquake motions.

In semi-active variable stiffness damper (SAVSD), switching control law (Yang et al., 2000) and modified switching control law (Xinghua, 2000) are considered in which its performance is based on the information of structural displacement and velocity. The damper force \(f_{di}\) at \(i^{th}\) location can be calculated as
\[
f_{di} = K_{di} \ddot{v}_i
\]
(6)

where \(K_{di}\) is the \((n \times n)\) effective stiffness matrix for SAVSD installed in the \(i^{th}\) damper location, in which \(K_{di}\) is zero, except for \(K_\alpha (i - 1, i) = -k_m, \ddot{x}_i\) is the drift at location of damper; and \(v_{di}\) is based on switching control law for the SAVSD installed in the \(i^{th}\) location. Here, the effects of optimal damper stiffness ratio based on the different configurations of damper placement under different earthquake motions are investigated. Praveen et al., 2013 studied the response of piping system with SAVSD under tri-directional seismic excitation. Parametric study is made in variation of \(\alpha\) in the range 0 to 0.06 and observed that the parameter \(\alpha\) plays an important role in the piping system responses. It is observed that there is significant reduction in responses such as displacement and base shear in the range of 78 to 79.2% and 37.4 to 40.6%, respectively for the piping system with SAVSD in Z-direction at D1 under the different earthquake motions.
It is observed from the Fig.7 that good amount of energy is absorbed by the dampers under all the earthquake motions. It is observed from Fig.8 that semi-active dampers are very effective in reducing the seismic response of the piping system.

6. Conclusions

Based on the investigation carried out in this study on seismic response control of the piping system, the following major conclusions are drawn:

1) It is seen that passive and semi-active supplemental devices are very effective in reducing the seismic response of piping system.

2) Natural frequency of the piping system increases with XPD and VE damper as stiffness is added in the piping system whereas in case of the fluid viscous damper it is unaffected. Inclusion of
viscous and VE dampers in the piping system significantly increases the modal damping of the piping system.

3) The response of the piping system decreases with increase in both, the mass ratio and the damping of the main system. For the same mass ratio and damping in the piping system, the MTMD is found to be more effective than single TMD.

4) An optimum value of the voltage input depending upon the damper locations in MR damper. Bang-bang control algorithm performed better than Lyapunov control algorithm.

5) The evaluated optimum parameter, $\alpha$, in the range of 0.4 to 0.7 of the predictive control law for the SAVFD and , of switching control law and modified switching control law for the SAVSD are found to be very effective in reducing the seismic responses for the piping system.

6) Experimental results of piping system with XPD are very well matched with analytical results. Remaining Passive damper and Semi-active damper results shown are analytical results. However, it is proposed to conduct experiment with Semi-active dampers.

References


