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A Study on Application of Tuned Mass Damper to Piping System under Earthquake

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1. Introduction

A Tuned Mass Damper (TMD) is one of the most widely used devices for the structural vibration control. The concept of vibration control using the TMD began in 1909 when Frahm developed a vibration control device called a dynamic vibration absorber. Although the TMD is the oldest concept of structural vibration control, it is applied in many fields today. Examples of these various TMD applications include, but are not limited to civil / architectural / mechanical structural systems such as bridges, high-rise buildings, control towers, and mechanical structures. In this study, the applicability of the TMD to piping system under seismic load was investigated through comparison of seismic responses.

2. TMD design

A TMD is a vibration absorber that soaks up the main vibration of the structure into the TMD by attaching an auxiliary device composed of mass, spring, and damper to the target structure. The TMD design is achieved through a method of finding the TMD stiffness and damping coefficient values that minimize the dynamic amplification factor (the ratio of dynamic maximum response and static maximum response of the structure) of the two-degree-of-freedom system that consists of the SDOF (Single-Degree-of-Freedom) structure-SDOF TMD device. The dynamic amplification factor of the structure under the harmonic excitation considering the damping on structure can be expressed as follows [1]:

$$R = \frac{X_{\max}}{X_{st}} = \frac{\sqrt{\left(1+\Delta\mu-\frac{\beta^2}{f^2}\right)^2 + 4\left(\frac{\zeta_d \beta}{f}\right)^2 (1+\Delta\mu)^2}}{Z} \qquad (1)$$

$$Z = f\left(\beta, f, \mu, \zeta, \zeta_d\right), \Delta = \begin{cases} 1 & \text{for base excitation} \\ 0 & \text{for main mass excitation} \end{cases}$$

where, β is a frequency ratio of external excitation and structure; f is a frequency ratio between structure and TMD; μ is a mass ratio between structure and TMD; ζ is a structural damping ratio; ζ_d is a TMD damping ratio. On the other hand, in the case of multi-degree-of-freedom structure-TMD system, structural mode which is targeted for the response reduction can be replaced by SDOF system, and based on such SDOF structural system, if TMD is attached to this system, TMD design can be similarly achieved using the above equation.

3. Application of TMD to piping system

In this study, we investigates how much the system response is reduced to some extent when applying the TMD to piping systems under earthquake loading. For this, a benchmark system introduced in Bezler et al. [2] is taken into account as the target piping system. In this piping system, a 3.5-inch-diameter water pipeline connecting two end points at different heights is considered. Both ends of pipelines of different heights are anchored and the pipe between these ends is supported by the intermediate supports. Information about detailed modeling can be found in the reference [2] cited above. Fig. 1 and Table I show the FEM modeling shape and mode analysis results through ANSYS Workbench.

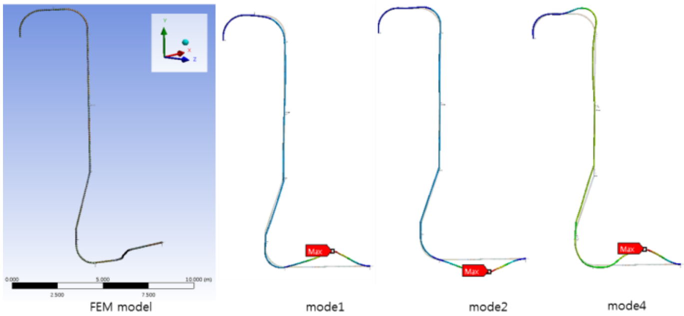
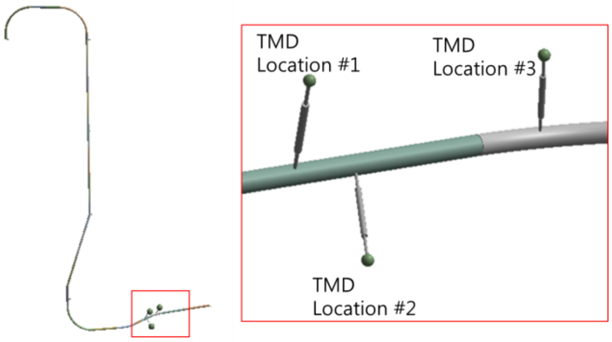


Fig. 1. Piping FEM model and mode analysis results

Table I: Summary of mode analysis results

Mode	Frequency	X-dir.	Y-dir.	Z-dir.
		Mass ratio	Mass ratio	Mass ratio
1	6.0096	1.06E-03	1.13E-03	**9.59E-02**
2	6.2415	1.30E-03	3.20E-03	**9.93E-02**
3	7.8603	2.31E-02	1.74E-04	3.59E-02
4	8.8025	1.76E-02	**0.592657**	7.08E-04
5	12.404	2.17E-03	8.26E-03	7.16E-03
6	12.813	7.02E-03	1.51E-03	7.89E-03
7	13.846	6.57E-02	1.76E-03	3.45E-02
8	15.159	1.99E-02	5.16E-03	9.19E-03
9	15.655	5.04E-03	5.74E-03	2.50E-02
10	17.815	8.75E-02	3.94E-02	6.85E-02
11	18.769	1.60E-03	1.43E-02	5.87E-02
12	22.025	3.86E-02	7.85E-03	0.145898
13	22.838	0.322448	4.97E-02	2.08E-02
14	24.820	3.14E-03	5.37E-04	2.93E-02
15	31.557	4.04E-03	8.81E-03	3.29E-04

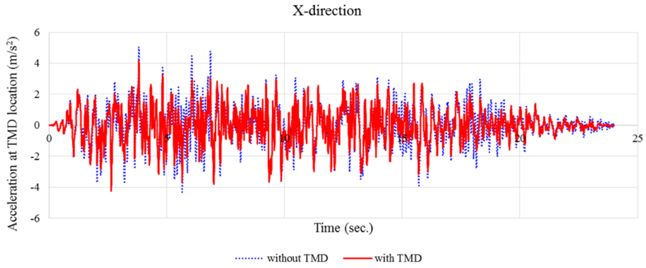
Since the dominant excitation frequency of a typical earthquake loading ranges from 1 to 10 Hz, the TMD is installed in the maximum response location of three modes (1st, 2nd, and 4th modes) with a relatively large mass participation ratio. For the TMD design, numerical optimization is used to minimize the dynamic amplification factor introduced in Eq. (1) regarding each mode. The detailed TMD installation locations and design values are shown in Fig. 2.



TMD Design from GA optimization				
Mode	Frequency (Hz)	Mass (kg)	Spring coeff. (N/m)	Damping coeff. (N-s/m)
1st	6.0096	4	4515.8	50.3
2nd	6.2415	4	4889.1	52.2
4th	8.8025	4	11739.8	34.0

Fig. 2. Locations of TMD installation in piping system

Let's look through how it affects the seismic performance of the target pipeline depending on the presence or absence of the TMD under actual earthquake excitation. For this purpose, as an input earthquake, we used the artificial earthquake time history load enveloping the design response spectrum (DRS) of the US NRC RG 1.60 [3] where the horizontal PGA is defined as 0.3g. As a result of the application, each directional acceleration response is compared in the time domain at the pipe element where TMD is located as shown in Fig. 3. As can be seen from the figure, it is observed that the overall acceleration responses decrease in time domain in all three directions due to TMD installation. Specifically, the TMD installation makes the original maximum response decreased by 11% in the x-direction and makes those decreased by 55% and 46% in the y- and z-directions, respectively. Here, the reason why the y- and z-direction maximum response reduction rate are relatively larger than the x-direction maximum response reduction rate seems because the mass participation ratio of y- and z-direction of the TMD installation target mode (i.e., 1st, 2nd, and 4th modes) is larger than that of x-direction.



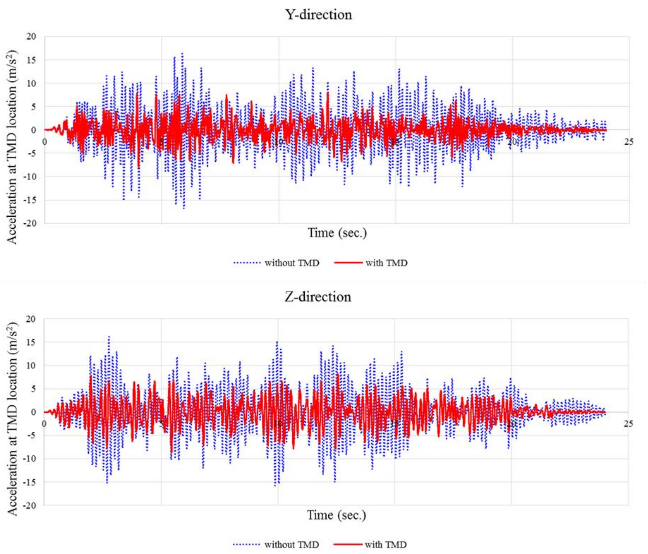


Fig. 3. Comparison of directional acceleration responses at TMD locations

4. Summary and conclusions

This study investigated how much the system response is reduced to some extent when applying TMD to piping systems under earthquake loading. Piping systems described in Bezler et al. (1985) was utilized for the TMD application. First, a mode analysis of the target pipeline was performed to determine the locations and number of TMD installation. As a result, a total of four modes were found in the dominant frequency band of the seismic load, and the first, second, and fourth modes with relatively large mass participation ratios were selected as the TMD installation locations. For the earthquake input, artificial earthquake time history loadings enveloping US NRC RG 1.60 DRS was considered. As a result of numerical analysis, it was confirmed that each directional acceleration response was reduced by 11% ~ 55% in the pipe element on the TMD installation locations.

ACKNOWLEDGEMENTS

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