Experimental research on vibration reduction of high-rise petrochemical equipment

W Hao¹, L D He, J Chang, W F Han and L X Wang

Diagnosis and Self-Recovery Engineering Research Center, Beijing University of Chemical Technology, Beijing 100029, P.R.China

E-mail: haowei611@163.com

Abstract. The wind-induced vibration of high-rise petrochemical equipment would do great harm to equipment operation and cause fatigue damage easily. Thus it is necessary to install some control device to reduce the vibration actively. Existing reinforcement methods include enlarging structural section, welding wind girder, adding braced frame system, fixing taut cable, etc. But each has some shortcomings. Therefore, the tuned mass damper (TMD), rarely used in high-rise petrochemical equipment, is studied by experiment to minimize wind-induced vibration, ensure safety operation and prolong service life. In the experiment, high-rise petrochemical equipment is properly simplified in order to verify the feasibility of the TMD. Parameters of the TMD are mainly researched, which include mass ratio and damping ratio. During the process, different mass ratios and damping ratios have been taken into account to understand the characteristics of the TMD under different conditions. By experiment, the changing tendencies of the natural frequency, damping ratio and top maximum displacement have been given after the simulator is implemented with the TMD. Experimental results show that the TMD is feasible for the wind-induced vibration control of high-rise petrochemical equipment, and that top maximum displacement of the simulator reduces by about 45% in the experimental condition. The experimental research has provided valuable preferences for practical application of the TMD in petrochemical field.

1. Introduction

For high-rise petrochemical equipment (figure 1), the ratio of height to diameter is larger, which leads to the greater flexibility and lower natural frequency. In various types of loads, wind load is most important for high-rise structure. Moreover, wind load results in 80% ~ 90% of the structure stress [1]. Due to larger height-diameter ratio and lower flexural rigidity, the intensive wind will have a greater effect on the vibration and deformation of high-rise petrochemical equipment. It will do great harm to safety operation and cause fatigue damage easily. Furthermore, the equipment service life could be shortened significantly. Therefore, it is necessary to install some control device to reduce the vibration actively.

Existing reinforcement methods consist of enlarging structural section, welding wind girder, adding braced frame system, fixing taut cable, etc. However, there are some disadvantages for them respectively, which are as follows:

¹ To whom any correspondence should be addressed.

Published under licence by IOP Publishing Ltd
• Enlarging structural section is a traditional wind-resistant design method to enhance the structure stiffness. If adopting this one, the diameter and wall-thickness of the equipment will increase a lot and it will also greatly increase the project cost certainly. Moreover, this method may exacerbate structural dynamic responses [2].
• Welding wind girder need to consider wall-thickness and load-bearing of petrochemical equipment. Stress concentration will be generated after welding wind girder. And the concave may appear after stress release, which will cause damage to petrochemical equipment.
• Although braced frame system has good ductility and high energy-dissipation, its stiffness is often not enough when the structure is higher. Meanwhile, both node-design and construction are also very complex, which will make steel and cost increase [3]. In addition, space limitation has to be considered carefully, too.
• Under intensive wind, structural vibration will make taut cable vibrate severely, which will lead to fatigue damage and connection damage. Consequently, the taut cable will lose the right role, which endangers the structure dramatically [4].

In contrast, the Tuned Mass Damper (TMD) has many advantages, such as low cost, small mass and size, vibration control of each direction, easy installation and maintenance, to be suitable for the wind-induced vibration control of high-rise structure especially [5]. However, the TMD is widely applied to TV tower, skyscraper, power transmission tower and bridge [6-9], rarely used in high-rise petrochemical equipment. Therefore, it is well worth researching that how the TMD is effectively applied to high-rise petrochemical equipment. So it is studied by experiment in this paper.

In accordance with the structural features of actual high-rise petrochemical equipment, the authors plan to install the pendulous TMD on the equipment, shown in figure 2. This type of TMD consists of sling, ring mass and damper. When wind load starts to work on the high-rise equipment, the TMD will come into play. Generated inertial force will act on the equipment when ring mass begins to swing relative to the equipment. It will lead to the resonance when the pendular frequency of TMD approaches the natural frequency of the equipment. At that time, the TMD can absorb part of vibration energy to reduce the wind-induced vibration of high-rise equipment. Then the dampers jointed with ring mass will dissipate the energy absorbed so as to achieve the purpose of wind-induced vibration control. In view of this principle, high-rise petrochemical equipment is simplified properly and then studied by experiment. In order to study control effect of different parameters, the wind-induced vibration is compared before and after the using of the TMD.

![Figure 1. High-rise petrochemical equipment.](image1)

![Figure 2. Vibration reduction with TMD schematic.](image2)

![Figure 3. Calculation diagram.](image3)
2. Wind-induced vibration control principle
In this analysis, high-rise petrochemical equipment can be simplified as a cantilever structure with \( n \) degrees of freedom, as shown in figure 3. And then the structure vibration can be formulated as follows:

\[
M \ddot{x} + C \dot{x} + K x = P(t) + P_T
\]  

(1)

where \( x = (x_1, x_2, \ldots, x_n)^T \) is a vector containing the displacements of the cantilever structure with respect to the ground. \( \dot{x} \) and \( \ddot{x} \) are respectively the velocity and acceleration vectors. \( M, C \) and \( K \) are the mass, damping and stiffness matrices of the structure. \( P(t) = (P_1, P_2, \ldots, P_n)^T \) is the wind load vector, which is the random function of time. And finally \( P_T = (0, \ldots, C_T(\dot{x}_1 - \dot{x}_j), \ldots, 0)^T \) is the force vector of the TMD, acting on the \( j \)-th degree of freedom of the structure.

The swing of the ring mass is relatively smaller, which can be approximated as a horizontal reciprocating motion. Therefore, the motion equation of the TMD is:

\[
M_T \ddot{x}_T + C_T (\ddot{x}_T - \dot{x}_j) = 0
\]

(2)

where \( M_T \) and \( C_T \) are the mass and damping of the TMD respectively, \( \ddot{x}_T \) and \( \dot{x}_T \) are the acceleration and velocity of ring mass relative to the ground, and \( \dot{x}_j \) is the actual velocity of the \( j \)-th degree of freedom of the structure.

To simplify calculation and decouple (1) easily, the matrix \( C \) is assumed to be the proportional damping matrix. Using the mode superposition method, namely \( x = \Phi x_p \), equation (1) is transformed into:

\[
M \Phi \ddot{x}_p + C \Phi \dot{x}_p + K \Phi x_p = P(t) + P_T
\]

(3)

where \( \Phi = (\varphi_1, \varphi_2, \ldots, \varphi_n) \) is the modal matrix, and \( x_p = (x_{p1}, x_{p2}, \ldots, x_{pn})^T \) is the principal coordinate vector.

Then

\[
\Phi^T M \Phi \ddot{x}_p + \Phi^T C \Phi \dot{x}_p + \Phi^T K \Phi x_p = \Phi^T P(t) + \Phi^T P_T
\]

(4)

\[
M_p \ddot{x}_p + C_p \dot{x}_p + K_p x_p = \Phi^T P(t) + \Phi^T P_T
\]

(5)

where \( M_p = \text{diag}(M_{p1}, M_{p2}, \ldots, M_{pn}) \) is the principal mass matrix, \( C_p = \text{diag}(C_{p1}, C_{p2}, \ldots, C_{pn}) \) is the modal damping matrix, and \( K_p = \text{diag}(K_{p1}, K_{p2}, \ldots, K_{pn}) \) is the principal stiffness matrix.
Expanding
\[
M_p \ddot{x}_p + C_p \dot{x}_p + K_p x_p = \phi_i^T P(t) + \phi_i C \left( \dot{x}_i - \ddot{x}_j \right) \quad i = 1, 2, \cdots, n
\]
\[
\ddot{x}_i + 2\xi_i\omega_i \dot{x}_i + \omega_i^2 x_i + \mu_i \phi_j \dddot{x}_i = F_i(t) \quad i = 1, 2, \cdots, n
\]
where
\[
\omega_i = \sqrt{\frac{K_{pi}}{M_{pi}}} \text{ is the } i\text{-th natural frequency;}
\]
\[
\xi_i = \frac{C_{pi}}{2\sqrt{K_{pi}M_{pi}}} \text{ is the } i\text{-th damping ratio;}
\]
\[
\mu_i = \frac{M_i}{M_{pi}} \text{ is the } i\text{-th mass ratio;}
\]
\[
F_i(t) = \frac{\phi_i^T P(t)}{M_{pi}} \text{ is the } i\text{-th external load;}
\]
\[
\phi_{ij} \text{ is the } j\text{-th element of the } i\text{-th modal vector.}
\]

For (8), time history analysis or response spectrum analysis can be used for the numerical solution to get the displacement response of each degree of freedom of the structure to study the wind-induced vibration control effect of the TMD assembled on high-rise petrochemical equipment.

3. Experimental system

Experimental system mainly consists of the simulator, fan, TMD, computer, eddy-current sensors and OR38 dynamic signal analyzer, shown in figure 4 and figure 5.

The simulator includes windward baffles, additional mass and supporting tube. Among them, the windward baffle bears simulated wind from the fan and drives the supporting tube to swing, which simulates the wind-induced vibration of high-rise petrochemical equipment. Besides, additional mass strengthens the swing of the simulator. The length, diameter and thickness of supporting tube are 1020mm, 32mm and 2mm respectively. The weight of the simulator is 43kg. And its natural frequency is 1.6 Hz by measuring.

In this experiment, the TMD consists of a sling, ring mass and damping liquid. The pendular frequency of the TMD is approximately determined by the single pendulum period formula, namely
\[
f = \frac{g}{l} \frac{1}{2\pi}
\] When the frequency \(f\) is 1.6 Hz, the length \(l\) is 97 mm, which determines the length of the sling initially. And then ensure that the frequency of the TMD is 1.6 Hz through adjustment.
The sensors will start to work in both x and y directions when the simulator swings under simulated wind. Collected signals are transmitted to OR38 analyzer and then displayed, recorded and processed by the computer.

4. Results and discussion

The parameters mainly include frequency ratio, mass ratio of the TMD to the primary structure and damping ratio of the TMD itself. When frequency ratio is about 1, the control effect of the TMD is best \[10,11\]. Therefore, mass ratio and damping ratio are researched by adjusting ring mass and damping liquid of the TMD to make the TMD absorb more energy and minimize the vibration. In the experiment, the wind-induced vibration of the simulator without TMD will be regarded as the benchmark.

The different ring masses are made up with various types of nuts, shown in figure 6. The mass ratio of the TMD to the simulator is 0, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10%. Among them, the number 0 means there is no TMD installed on the simulator.

The different damping liquids are made up of pulverized carbon fibre sheet and L-TSA32 turbine lubricant according to different concentrations, such as 0%, 0.25%, 0.50%, 0.75% and 1.00%, as shown in figure 7. Among them, the number 0% means there is no pulverized carbon fibre sheet in the lubricant. And the viscosity of the damping liquid is increasing with increased concentration.

![Figure 6. Nuts with different mass.](image)

![Figure 7. Damping liquids with different viscosity.](image)

Under a certain concentration of damping liquid, mass ratio will be increased from 1% to 10% in turn when doing the experiment to study vibration control effect of the TMD in different conditions. In order to minimize errors, the experiment in each condition will be repeated 5 times to get the average. And the vibrations in two directions will be synthesized to obtain the actual top displacement of the simulator.

4.1. The effect of the TMD on natural frequency of the simulator

Through initial displacement disturbance applied, the simulator will do damped free vibration under the effect of damping. According to the formula \[ f_d = f_0(1 - \xi^2)^{1/2} \], it can be seen that the natural frequency \( f_n \) can be instead of the frequency \( f_d \) of damped free vibration when damping ratio \( \xi \) is smaller (\( \xi \) is 10\(^{-1}\) order of magnitude measured in this experiment\(^1\)). Therefore, the natural frequency of the simulator can be obtained according to damped free vibration curve recorded. Figure 8 shows the changing tendency of natural frequency of the simulator after installation of the TMD.

The experimental results show that the natural frequency of the simulator is almost unchanged with increased concentration of damping liquid, but declines slowly and linearly with increased mass ratio merely. When mass ratio is 10%, the natural frequency reduces by about 3.75%. Therefore, the effect of the TMD on the natural frequency of high-rise petrochemical equipment can be neglected when designing the TMD.
4.2. The effect of the TMD on damping ratio of the simulator

According to time-domain waveform of damped free vibration, damping ratio of the simulator can be calculated with the free vibration method. Figure 9 shows the changing tendency of damping ratio of the simulator after installation of the TMD.

The experimental results show that damping ratio of the simulator rises rapidly after installation of the TMD. The curve is steeper at the beginning and then flattens out slowly after about 8% mass ratio. The damping ratio of the simulator increases significantly with increased mass ratio. Meanwhile, the
increasing extent of damping ratio first increases and then decreases with increased concentration of damping liquid, which is maximal when 0.75% concentration. The damping ratio increases 8 times nearly when 10% mass ratio and 0.75% concentration, which is of great benefit to the vibration control of high-rise petrochemical equipment.

4.3. The effect of the TMD on top maximum displacement of the simulator

Figure 10 shows the changing tendency of top maximum displacement of the simulator after installation of the TMD.

Figure 10. The changing tendency of top maximum displacement of the simulator after installation of the TMD.

Figure 11. Comparison between time-domain waveforms under different conditions.
It can be seen from figure 10 that top maximum displacement of the simulator decreases rapidly after installation of the TMD. The curve is steeper at the beginning and then flattens out slowly after about 3% mass ratio. The top maximum displacement of the simulator decreases significantly with increased mass ratio. Meanwhile, the decreasing extent of top maximum displacement first increases and then decreases with increased concentration of damping liquid, which is maximal when 0.75% concentration. The top maximum displacement decreases 45% nearly when 10% mass ratio and 0.75% concentration.

Figure 11 shows the time-domain waveforms under different conditions in one measurement, in which the TMD is 10% mass ratio and 0.75% concentration. It can be seen from figure 11 that wind-induced vibration of the simulator has been controlled effectively after installation of the TMD.

5. Summary and conclusions
In this work, the effectiveness of the TMD used for the vibration control of high-rise petrochemical equipment under intensive wind has been investigated. The main conclusions are as follows:

- After installation of the TMD, the changing tendency of natural frequency of the simulator is linear to the mass of the TMD merely. The change of the natural frequency is not obvious and even negligible. Therefore, the effect of the TMD on the natural frequency of high-rise petrochemical equipment can be neglected when designing the TMD.

- After installation of the TMD, the damping ratio of the simulator increases significantly. This is very beneficial to the wind-induced vibration control.

- When the concentration of damping liquid is 0.75%, the decreasing extent of top maximum displacement of the simulator is maximal. Therefore, the viscosity of damping liquid should be moderate, namely not the bigger the better, when designing the TMD. In other words, there is an optimal damping ratio for the vibration control.

- The decreasing extent of top maximum displacement of the simulator flattens out slowly after about 3% mass ratio. Given bigger weight and limited load-bearing capacity of high-rise petrochemical equipment, there will be many problems for the processing, transportation and installation of the TMD if the mass of the TMD is too large. So it is recommended to take 3% to 5% mass ratio.

In a word, the TMD is very feasible for the wind-induced vibration control of high-rise petrochemical equipment. However, to meet the requirements of practical application still needs to consider some other factors and to investigate the TMD further.

Acknowledgments
The authors gratefully acknowledge the financial support provided by Joint Project Special Fund of Education Committee of Beijing, the Ph. D. Programs Foundation of Ministry of Education of China (20110010110009) and the Major State Basic Research Development Program of China (“973” Program) Projects (2012CB026000).

References
[1] Li S 2009 Petrochemical Design 26 14–6
[2] Hu X J and Ge J P 2007 Shanxi Architecture 33 81–2
[3] Luo R 2001 Steel Construction 16 47–50
[4] Jin L, Ying Z G and Luo Y M 2004 Noise and Vibration Control 24 5–7
[5] Qin L, Yan W M, Hu X J and Nie W Z 2009 Journal of Beijing University of Technology 35 761–8
[6] Huang R X, Li A Q, Zhang Z Q, Fan Z and Liu X M 2009 Journal of Southeast University (Natural Science Edition) 39 519–24
[7] Ren J, Teng J and Ye L P 2003 Earthq. Eng. Eng. Vib. 23 187–93
[8] Li L, Xia Z C, Zhang H and Liang Z P 2007 *J. of HUST. (Urban Science Edition)* 24 4–7
[9] Wang T C 2007 *Noise and Vibration Control* 27 28–30
[10] Lee C L, Chen Y T, Chung L L and Wang Y P 2006 *Eng. Struct.* 28 43–53
[11] Sgobba S and Marano G C 2010 *Mech. Syst. Signal. Pr.* 24 1739–55