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Experimental investigation on multi-mode vortex-induced vibration control of stay cable installed with pounding tuned mass dampers

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Abstract. In this paper, pounding tuned mass dampers (PTMDs) were designed to mitigate the multi-mode vortex-induced vibration (VIV) of stay cable utilizing the viscous-elastic material's energy-dissipated ability. The PTMD device consists of a cantilever metal rod beam, a metal mass block and a specially designed damping element covered with viscous-elastic material layer. Wind-tunnel experiment on VIV of stay cable model was set up to validate the effectiveness of the PTMD on multi-mode VIV mitigation of stay cable. By analyzing and comparing testing results of all testing cases, it could be verified that the PTMD with viscous-elastic pounding boundary can obviously mitigate the VIV amplitude of the stay cable. Moreover, the installed location and the design parameters of the PTMD device based on the controlled modes of the primary stay cable, would have a certain extent suppression on the other modal vibration of the stay cable, which means that the designed PTMDs are effective among a large band of frequency for the multi-mode VIV control of the stay cable.

Keywords: stay cable; cable-stayed bridge; pounding tuned mass damper (PTMD); vortex-induced vibration (VIV); multi-mode vibration control; viscous-elastic material

1. Introduction

Recently, Cable-stayed bridges have been constructed widely and rapidly due to their large stepping over ability, economical cost and elegant structural appearance. With the span of cable-stayed bridge enlarged, the length of stay cables in cable-stayed bridges increase greatly and its large amplitude wind-induced vibrations, such as wind-rain-induced vibration and multi-mode vortex-induced vibration (VIV) become prominent (Hover *et al.* 1997, Matsumoto *et al.* 1998, 2001). Especially, multi-mode vortex-induced vibration (VIV) of stay cables is one of the severe wind-induced vibrations, which happen frequently in cable-stayed bridges (Brika and Laneville 1993, Violette *et al.* 2007, Huera-Huarte and Bearman 2009, Chen *et al*. 2014). With the length of the stay cables increasing, it becomes more and more difficult for the damper installed at the near anchorage to provide enough additional damping to control the multi-mode VIV of the long-span stay cables (Li *et al.* 2007, 2008, Duan *et al.* 2005, 2006, Chen *et al*. 2004), though some novelty control devices and methods had been developed recently (Lu 2017, Duan *et al*. 2018, Or *et al*. 2008, Wang *et al.* 2005). In order to enhance the control efficacy and improve damping ability of the control devices, it is important for the control devices to be decentralized installed along the long-span stay cables. Some control devices, such as tuned mass dampers (TMD) and impact dampers et.al, are suitable to be decentralized installed along the stay cable.

The TMD is one of typical dynamic absorbers, which can effectively absorb the kinetic energy from the primary structures and suppress the primary structures' excessive oscillations. Since TMD was put forward, researchers all over the world have done lots of work on the theories and applications of TMD devices. Due to improve the robustness of single TMD, the dynamic performance of the multi-tuned mass damper (MTMD) is especially studied by Igusa and Xu (1994), Zuo and Nayfeh (2005), Li and Ni (2007). The multi-mode vibration control installed with MTMD were studied in the several past decades (Kareem and Sun 1987, Chang and Gu 2003). Their investigation indicated that the dual TMDs could reduce the vibration response effectively comparing to only using one TMD. Over the past decades, TMD had been widely accepted to suppress the wind-induced vibration control of flexible and low-damped structures (Warburton and Ayorinde 1980), such as high-rise buildings, transmission towers, pipeline structures, long-span bridges (Liu and Chang 2008, Tian *et al.* 2013, Cai and Wu 2007, Chen and Cai 2004, Lin and Cheng 2000) and so on. However, the absorbers have no inherent damping and is effective only among a small band of frequency. In order to solve the shortcomings of the absorbers, a certain amount of damping was introduced to the TMD by implementing viscous dampers, viscoelastic (VE) dampers, friction dampers and magneto rheological dampers (Ormondroyed and Den Hartog 1928, Zemp *et al*. 2011, Weber and Maslanka 2012). The implementations of theses dampers can make the TMD complicated and demand continual maintenance (Collette 1998).

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The pounding TMD (PTMD) was developed as an integrated combination of a TMD and an impact damper. During the PTMD design, the moving mass block is similar with that of a regular TMD, and a boundary covered with energy-dissipated materials to be impacted by the mass block. When the primary structure installed with the PTMD happens to vibrate, the mass block absorbs the kinetic from the primary structure and moves to impact or pound the boundary. Then the mechanical energy of the mass block will be dissipated by the pounding. Compared with the regular TMD, the PTMD can be conveniently installed and is relatively easy to be maintained and replaced (Collette 1998). The previously experimental and theoretical investigations of the dynamic performances of the PTMD indicates that the PTMD has lager energy dissipating capacity and more robust to the system uncertainty compared with the regular TMD (Ema and Marui 1994, Collette 1998, Li *et al.* 2015, Song and Zhang 2013, 2016). And the damping ability of the PTMD is effectively influenced by the pounding force and time, the stroke of the mass block and the mass ratio of the mass block to the primary structure (Ema and Marui 1994, Collette 1998, Cheng and Wang 2003, Li and Darby 2004, Cheng and Xu 2005). Previously studies also demonstrated that the PTMD can superiorly suppress the large amplitude vibration of the flexible and low-damped structures, such as transmission towers and pipeline structures et al. (Li *et al.* 2015, Song and Zhang 2013, 2016). However, there is a scarcity of experimental verification of the PTMD on wind-induced vibration control of stay cables.

In this paper, considering the advantages of the PTMD, such as decentralized installation, large energy dissipating capacity and almost maintenance-free, a wind-tunnel experiment on multi-mode vortex-induced vibration(VIV) of one stay cable model was set up to validate the effectiveness of the PTMD. The PTMD device consists of a cantilever metal rod beam, a metal mass block and a specially designed damping element (pounding boundary) covered with viscous-elastic material layer. The wind tunnel experiments on multi-mode VIV of the stay cable model were conducted to investigate the energy dissipating ability and control efficacy of the PTMD with different installations, quantity and pounding boundary. Under three testing conditions, such as without control, installation of the PTMD with metal pounding boundary and installation of the PTMD with viscous-elastic damping pounding boundary, the dynamic performances of the VIV of the stay cable model were all tested. By analyzing and comparing the testing results, it can be demonstrated that the PTMD with viscous-elastic pounding boundary can obviously mitigate the VIV amplitude of the stay cable model. Moreover, the installed location and the design parameters of the PTMD device based on the controlled modes of the primary stay cable, would have a certain extent suppression on the other mode vibration of the stay cable.

2. Experimental setup

The experimental stay cable model illustrated in Fig. 1 was set up in the Joint Laboratory of Wind Tunnel and Wave Flume located at Harbin Institute of Technology in China. The length and diameter of the cable model are 6.757 m and 0.066 m, respectively. The weight per meter of the cable model is 0.668 kg/m. The cable model was fixed on the rigid steel frame and was tightened with an axial tension force of 1278.7 N. The upper and lower ends of the cable model is 3.022 and 0.35 m from the floor. The inclined angle of the cable model is 25.5° and the yaw angle was set to 0° in the test. The theoretical natural frequency of the cable model is 3.494Hz.

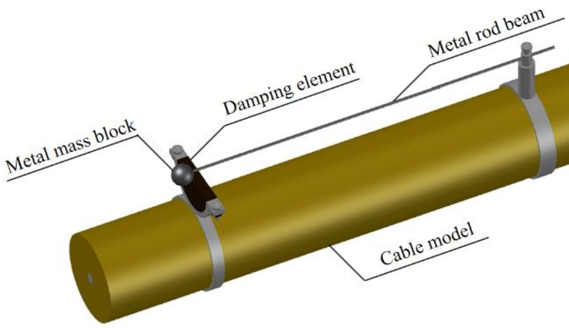
Four accelerometers were attached on the cable model to measure the cross-flow and out-plane vibration responses at two locations, which are the mid-span and quarter-span from the lower end of the cable model, respectively. Accelerometer 1 and accelerometer 3 were set to measure the cross-flow vibration at the mid-span and quarter-span of the cable model, respectively, and accelerometer 2 and accelerometer 4 were set to measure the out-plane vibration at the mid-span and quarter-span of the cable model, respectively. The sampling rate is 1000 Hz and the sampling time is 10 second for the four accelerometers.

Fig. 2 illustrated the typical PTMDs designed for the multi-mode VIV control of the cable model. The PTMD device consists of a cantilever metal rod beam, a metal mass block and a specially designed damping element (pounding boundary). The damping element consists of the curved steel sheet with a thickness of 2.0 mm covered with viscous-elastic material layer. The thickness of the viscous-elastic material layer is 28.0 mm. The cross-section of the damping element was shown in Fig. 3. The curved pounding boundary serves two purpose: one is to limit the stroke of the mass block, another is to dissipate the kinetic energy absorbed from the primary cable model. When the VIV of the cable model occurs, the metal mass block can impact the curved pounding boundary and the mechanical energy of the cable model is dissipated.

3. Design of the PTMDs

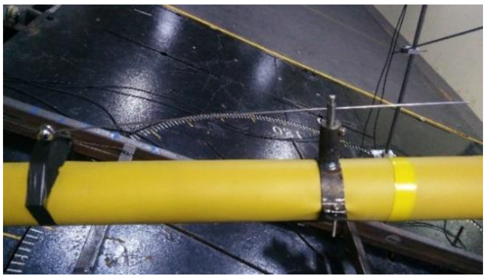
For the purpose of mitigating the multi-mode VIV of the cable model, one PTMD (named PTMD-1) designed to control the first modal VIV of the cable model was installed at the mid-span of the cable.

Fig. 1 The experimental setup of stay cable model



(a) Schematic diagram of PTMD

(b) PTMD-1 installed at the mid-span of the cable model



(c) PTMD-2 installed at the one-fourth and three-fourth span of the cable model

Fig. 2 Design and installation of PTMDs in the experiments

Another two same PTMDs (named PTMD-2) designed to control the second modal VIV of the cable model were respectively installed at the three-fourth span and one-fourth span of the cable. During the experiment, two categories of PTMDs to control the first and second modal VIV of the cable model were designed as shown in Fig. 2, respectively.

In order to achieve the superior control efficacy, the optimum frequency of the PTMD should be designed according to the controlled modal VIV of the cable model. The optimum frequency ω_a of PTMD can be expressed as follows (Ormondroyed and Den Hartog 1928)

$$\omega_a = \beta_a \omega_n \tag{1}$$

$$\beta_a = \omega_a / \omega_n = \sqrt{1-0.5\mu} \big/ (1+\mu) \tag{2}$$

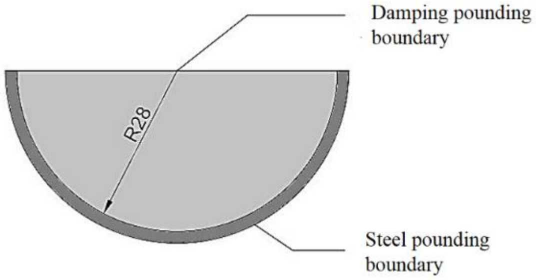


Fig. 3 Schematic cross-section of pounding boundary of PTMD

where β_a is the optimum frequency ratio between the optimum frequency ω_a of the PTMD and the modal frequency ω_n of the cable; μ is the modal mass ratio of the mass block of the PTMD to the modal mass of the controlled vibration mode of the cable model.

The cable dynamics is descripped as the motion of taut string with an assumption of small sag and high tension-to-weight ratios in the cable, the modal mass M of the cable is calculated using the following formula:

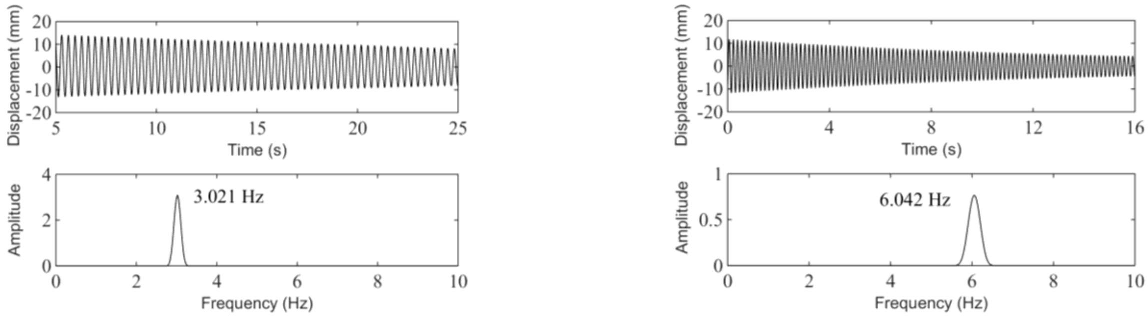
$$M = [m_{ij}] \tag{3}$$

$$m_{ij} = m\int_0^L \phi_i(x)\phi_j(x)dx = mL/2 \tag{4}$$

$$\Phi_n = sin(n\pi x/L) \tag{5}$$

where $\emptyset_n$ is the shape function of the *n*th mode of the cable at the any point *x* away from the end, *L* is the length of the cable, *m* is the mass per unit length of the cable and *n* is the *n*th mode order of the cable vibration.

When the mass ratio μ of two categories of PTMDs is both assumed to be 5%, and according to Eqs. (1)-(5), the optimum frequency ratio β_a is 0.94 and the mass block of two categories of PTMDs could be calculated to be 0.10 kg. On the basis of the modal frequencies of the cable model without control, which were obtained from the free vibration tests presented in the section 5.1, the optimum frequencies of the PTMDs for controlling the first modal VIV and second modal VIV of the cable model are 3.278 and 6.491 Hz, respectively. The length and cross-section size of the metal rod of the PTMD connected with the mass



(a) PTMD-1 (b) RTMD-2

Fig. 4 Free vibration responses of two types of PTMDs

block were designed on the basis of the modal frequency formula of a cantilever beam and the optimum frequency of the PTMD. In the experimental study and for the PTMD-1 illustrated in Fig. 2(b), the metal mass block is a steel ball with a diameter of 0.016 m and the connected metal rod is a cantilever beam with a length of 0.41 m. The designed PTMD-1 was installed at the mid-span of the cable model to suppress the first modal VIV of the cable model. For the second modal VIV mitigation of the cable model, the length of the connected metal rod of the PTMD was calculated to be 0.26 m, which is named as PTMD-2 and illustrated in Fig. 2(c). Two PTMDs-2 was installed at the quarter-span and three-fourth span of the cable model. The diameter of the connected metal rod of two categories of PTMDs was both 0.002 m.

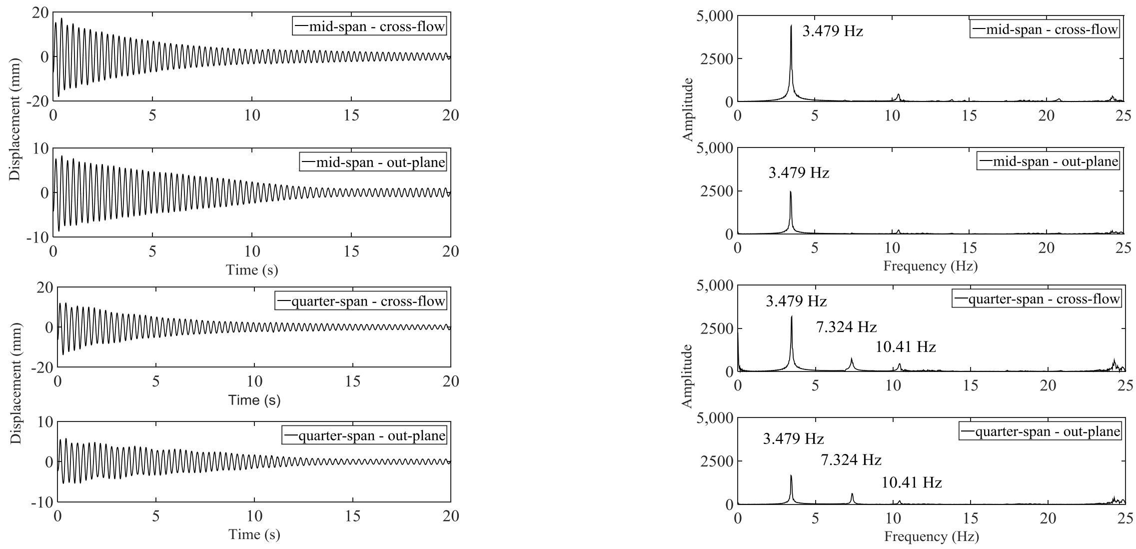
4. Testing conditions

Before the experiments on the VIV control of the cable model installed with PTMDs, the free vibration tests of the cable model installed without/with PTMDs were carried out to obtain the modal frequency of the cable without/with control corresponding to each testing cases. These modal frequencies obtained from the tests would be utilized to design the PTMDs and calculate the corresponding wind speed of the VIV of the cable model, which is the instruction to adjust the wind speed during the wind tunnel tests. The detailed testing cases were included as the following: (1) First case is without control named as un-control. (2) Second case is the first modal VIV control of the cable model named as case C1. (3) Third case is the second modal VIV control of the cable model named as case C2. (4) Fourth case is combined control the first and second modal VIV of the cable model named as case C3. (5) For each PTMD, two different pounding boundaries were tested respectively: one is damped pounding that the viscous-elastic material layer serves as the pounding boundary. Another is rigid pounding that the curved steel sheet serves as the pounding surface. Corresponding to each testing cases for controlling (case C1, case C2 and case C3), the PTMD impacts the rigid pounding boundary named as cases S which were called case C1-S, case C2-S and caseC3-S respectively, and the PTMD impacts the damped pounding boundary named as cases D, such as case C1-D, case C2-D and case C3-D respectively. For the case C1, one PTMD-1 was fixed at the mid-span of the cable model where the displacement amplitude of the first modal VIV is peak value. For the case C2, two PTMDs-2 were located at the quarter-span and three-fourth span of the cable model where the displacement amplitudes of the second modal VIV are peak values. For the case C3, three PTMDs included one PTMD-1 and two PTMDs-2 were installed at the previous locations of the cable model.

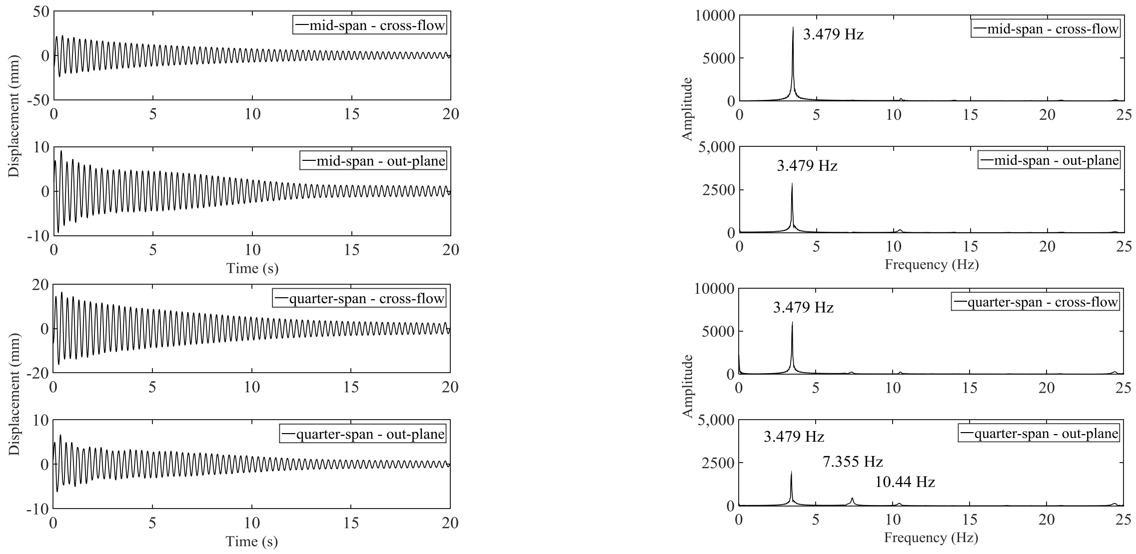
5. Experiment results

5.1 Modal frequency of PTMDs and cable model without/with PTMDs

The free vibration experiments on the cable model installed without/with PTMDs were carried out to get the modal frequencies and the first/second modal damping ratios of the cable corresponding to each testing case, prior to the experiments on the VIV control of the cable model. For the first modal free vibration experiments of the cable model without/with PTMDs, an initial displacement excitation was exerted at the mid-span of the cable model, then releasing. The second modal free vibrations of the cable model without/with PTMDs were excited by exerting an initial displacement at the quarter-span of the cable model. Corresponding to each testing case, the cross-flow and out-plane displacement time-history at the mid-span and quarter-span of the cable model were acquired by laser displacement meters. The modal damping ratios were determined by using the logarithmic decrement method based on the displacement time-history. The spectrum of the displacement responses was analyzed to identify the vibration frequencies of the cable mode. For the first modal free vibration of the cable model installed with PTMD-1 at the mid-span and corresponding to testing cases C1-D and C1-S, the displacement time-histories and spectrum analysis were shown in Fig. 5. The experimental results of the other testing cases were similar with that shown in Fig. 5, and the other testing results were not presented here. Under each testing case, the identified modal frequencies and damping ratios of the cable without/with PTMDs were shown in Table 1 and 2, respectively. As shown in Fig. 5 and Table 1 and 2, it can be seen that the installation of PTMD slightly



(a) PTMD-1



(b) PTMD-2

Fig. 5 Free vibration responses of the cable model at different case

changes the modal frequency of the cable model, but increases the modal damping ratio of the cable model by 75.56%. Moreover, the PTMD with damped pounding boundary adds more damping to the cable than that of the PTMD with rigid pounding boundary due to the viscoelastic material layer dissipating the mechanical energy absorbed from the cable model vibration.

5.2 VIV of cable model without control

Before the PTMDs were installed, the modal frequencies and corresponding wind speeds of the VIV of the cable model were tested. On the basis of the testing results, which are the cross-flow vibration accelerations measured by the accelerometers and the wind speeds measured by the hotwire anemometry, the modal frequencies and corresponding wind speeds of the VIV of the cable model is shown in Table 3.

5.3 VIV Control of cable model installed with PTMDs

By changing wind speed step by step and based on the calculated wind speed of the VIV of the cable model according to the tested modal frequency of the cable model listed in Table 1, the first three modal VIV of the cable model was excited in wind tunnel and a series of tests were carried on corresponding to each testing case listed in section 4. Under different wind speeds, the cross-flow and out-plane acceleration time-histories at the mid-span and quarter-span were acquired respectively. Utilizing the numerical integration approach and according to the collected acceleration time-histories, the cross-flow and out-plane displacement time-histories at the mid-span and quarter-span were obtained respectively. For each testing case and each wind speed, the maximum displacement amplitude was seek out from the corresponding displacement time-histories. Under different wind speed, the cross-flow displacement amplitude of the cable at the mid-span and quarter-span are shown in Fig. 6, which displayed the control effect on the first three modal VIV of the cable corresponding to different testing cases.

As shown in Fig. 6(a), for the testing case C1, when the wind speeds are 1.671 and 3.156 m/s, the cable model behaves in the first and third modal VIV respectively, as same as that of the un-control cable model. In testing case C3, the wind speed of the third modal VIV of the cable is decreased to 2.985 m/s because of the vibration frequency decreasing, when three PTMDs were installed and added mass to the cable model. By Comparing the displacement amplitude in different control cases as shown in Fig. 6(a), it shows that there are obvious control effects on the first and third modal VIV of the cable in case C1 and C3. Especially in case C3 that two categories of PTMDs were installed, the control efficacy is superior. Under the testing case C1, the control efficacies of the first modal and third modal VIV of the cable reach to 89% and 30%, respectively. And with the testing cases C3, these control efficacies are more than 90% and 70%, respectively. It could also be seen that the control efficacy of the PTMDs with the viscoelastic damping pounding boundary is much better than that of the PTMDs with the rigid pounding boundary. For the first modal VIV of the cable, the displacement amplitude under case C1-D is 0.25 times of that under case C1-S. And for the third modal VIV control, the displacement amplitude with case C3-D is nearly 0.5 times of that with case C3-S. It can be seen from Fig. 6(b) that the displacement amplitudes of the second modal VIV of the cable at the quarter-span is effectively reduced to 0.2 times and 0.3 times of these with un-control under testing case C2 and case C3, respectively. Especially, when the PTMDs with the viscoelastic damping pounding boundary were installed for testing case C2-D and case C3-D, the PTMDs could achieve superior control efficacy which is more than 80%, due to the damping energy-dissipated. However, the PTMDs with the same pounding boundary, such as case C2-S &case C3-S and case C2-D & case C3-D, have almost same control efficacy respectively. It means that the PTMD-1 fixed at the mid-span of the cable plays no role on controlling the second modal VIV of the cable. Under case C2 and case C3, the first modal VIV of the cable could be suppressed in certain. Moreover, as shown in Figs. 6(a) and 6(b), the designed PTMDs for the first and second modal VIV control could certainly suppress the third modal VIV of the cable model. These testing results demonstrates that the designed PTMDs are effective among a large band of frequency for the multi-mode VIV control of the stay cable.

Corresponding to the first three modal VIV of the cable and under each testing cases listed in section 4, the out-plane displacement amplitude of the cable was shown in Fig. 7. As shown in Fig. 7 and corresponding to the wind speeds that the first three modal VIV of the cable happened, the peak values of the out-plane displacement of the cable are much smaller than that of the VIV of the cable. By comparing the testing results shown in Fig. 7 to that of shown in Fig. 6, it can be seen that the influence of the PTMDs' installation on the control efficacy of the out-plane displacement responses of the cable is almost same as that of the cross-flow displacement responses of the cable.

In order to indicate whether the PTMD-1 installed at the mid-span of the cable (case C1) affects the second modal VIV of the cable or not, as shown in Fig. 8, the cross-flow displacement response at the quarter-span of the cable under testing case C1 was compared to that of un-control case. Similarly, on the purpose of studying whether the PTMD-2 under case C2 affect the first modal VIV of the cable, as shown in Fig. 9, the cross-flow displacement response at the mid-span of the cable under case C2 was also obtained and compared to that of un-control case. The cross-flow displacement amplitude at the quarter-span of the cable corresponding to different wind speeds under case C1 shown in Fig. 8 indicated that the control effects of the PTMD-1 on the second modal VIV of the cable are not obvious, just increase the wind speed which the VIV of the cable happened.

Table 1 First three modal frequencies of cable model without/with PTMDs

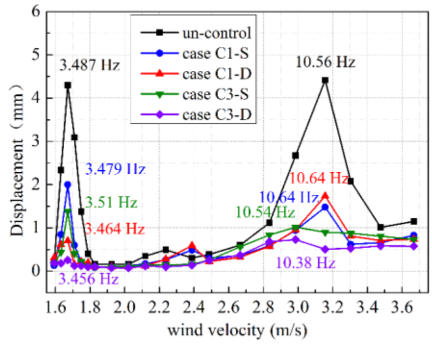
Testing case	1st mode frequency (Hz)		2nd mode frequency (Hz)		3rd mode frequency (Hz)	
	Cross-flow	Out-plane	Cross-flow	Out-plane	Cross-flow	Out-plane
Un-control	3.49	3.49	6.91	6.91	10.56	10.56
Case C1-D	3.48	3.48	7.32	7.32	10.41	10.41
Case C1-S	3.48	3.48	7.36	7.36	10.44	10.44
Case C2-D	3.48	3.48	6.86	6.86	10.41	10.41
Case C2-S	3.48	3.48	6.83	6.83	10.41	10.41
Case C3-D	3.47	3.47	6.83	6.83	10.41	10.41
Case C3-S	3.46	3.46	6.76	6.76	10.38	10.38

Table 2 Modal damping ratios of cable model without/with PTMDs

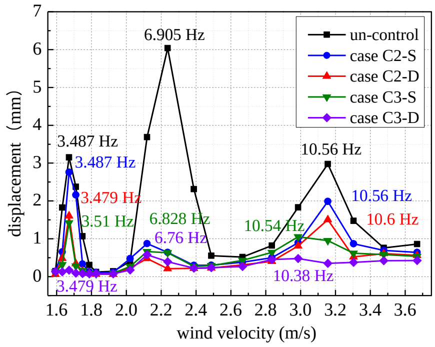
Testing case	1st mode damping ratio (%)		2nd mode damping ratio (%)	
	Cross-flow	Out-plane	Cross-flow	Out-plane
Un-control	0.45	0.45	0.45	0.45
Case C1-D	0.59	0.53	/	/
Case C1-S	0.50	0.49	/	/
Case C2-D	/	/	0.65	0.58
Case C2-S	/	/	0.63	0.56
Case C3-D	0.79	0.74	/	/
Case C3-S	0.66	0.61	/	/

Table 3 Modal frequencies and corresponding wind speeds of the VIV of the cable model

VIV	1st mode		2nd mode		3rd mode	
	f	v	f	v	f	v
	3.49	1.68	6.91	2.20	10.56	3.10

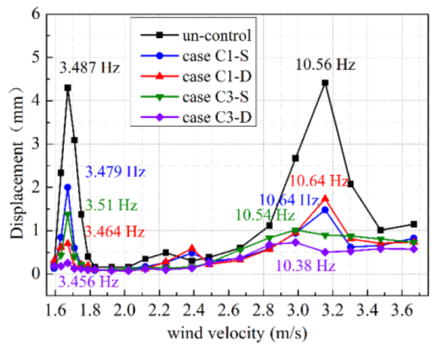


(a) Mid-span

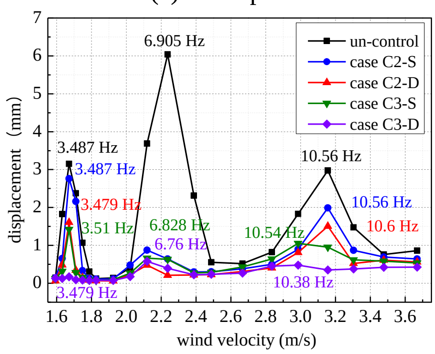


(b) Quarter-span

Fig. 6 Cross-flow displacement amplitude at different location of the cable



(a) Mid-span



(b) Quarter-span

Fig. 7 Out-plane displacement amplitude at different location of the cable

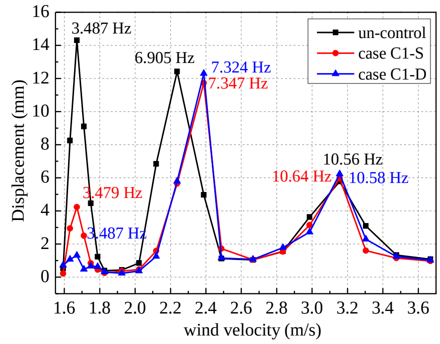


Fig. 8 Cross-flow displacement response at quarter-span of the cable installed with the PTMD-1 at mid-span

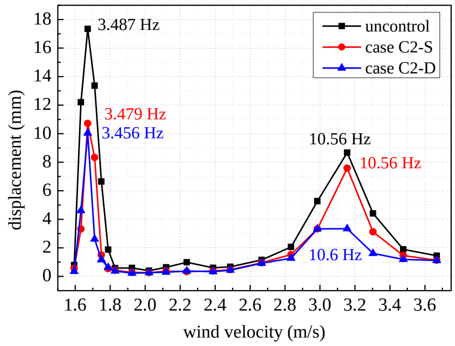


Fig. 9 Cross-flow displacement response at mid-span of the cable installed with the PTMDs-2 at quarter-span

At the same time, the control effects of the PTMD-1 under case C1-D and C1-S on the third modal VIV of the cable at the quarter-span are also insignificant. As shown in Fig. 9, it shows that the PTMDs-2 under case C2-D and case C2-D also have some effect on the first and third modal VIV of the cable. On the basis of the testing results shown in Figs.8 and 9, it could be seen that the designed PTMDs with the optimum frequencies should be installed at the location with the peak displacement response to enhance its control efficacy

6. Conclusions

In this paper, based on viscous-elastic material's energy-dissipated ability and utilizing the PTMD devices, wind tunnel experimental investigation on the multi-mode VIV control of the stay cable model was carried out to demonstrated the effectiveness of the PTMD devices on the multi-mode VIV of stay cables. From the systemically experiments, the following conclusions could be drawn.

- The designed two PTMD categories on the basis of the first two mode frequencies of cable could effectively mitigate the first two mode VIV of cable. And the third modal VIV of the cable could also be suppressed certainly, which demonstrates that the designed PTMDs are effective among a large band of frequency for the multi-mode VIV control of the stay cable. Moreover, the PTMDs with the viscous-elastic damping pounding boundary have a great effect on energy dissipation and reducing the multi-mode VIV of the cable.

- The designed PTMDs could control both the cross-flow and out-plane vibration of the cable at the same time. When the cross-flow vibration responses of the cable are effectively controlled by the designed PTMDs under each testing case, the out-plane vibrations of the cable could be mitigated though the vibration amplitudes are smaller than that of the cross-flow vibration.
- The influence of the installed locations and optimum frequencies of the PTMDs on the control efficacy of the multi-mode VIV of the cable, are obviously. The designed PTMD-1 according to the first modal parameters of the cable had no effect on the second, while the designed PTMD-2 according to the second modal parameters of the cable had a limited effect on the first and third modal VIV. For the purpose of enhancing the control efficacy, the PTMDs with the optimum frequencies should be installed at the location with the peak displacement response of the cable.

Declaration of Conflicting Interest

The Authors declare that there is no conflict of interest in preparing this article.

Acknowledgments

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