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Experimental investigations on effectiveness of viscous and viscous inertial dampers on reducing the multimodal vibrations of stay cables

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SUMMARY:
In order to validate the effectiveness of viscous dampers (VDs) and viscous inertial damper (VID) on mitigating the multimodal vibrations of stay cable, the additional damping provided by these dampers were tested in the laboratory. First, two plate eddy current dampers (PECDs), in which the damping coefficient can be conveniently adjusted, was specially designed and manufactured. The mechanical property of these PECDs were obtained by tests and numerical simulations. Second, the natural frequencies of a test stay cable were carefully determined by tests and numerical simulations, and the effect of cable sag were carefully analyzed. Third, a series of tests including 12 test cases were carried out to validate the effectiveness of a single VD, a single VID and two VDs. The inherent damping of the first 25 modes are in the range from 0.068% to 0.22%. It appears that low efficiency to simultaneously enhance the damping of the first 25 modes can be found by adding a single VD and a single VID. However, two VDs has a significant improvement on the damping of the first 25 modes, and should be considered to a reasonable countermeasure to simultaneously reduced the low-order rain-wind induced vibrations and high-order vortex induced vibration.

Keywords: Stay cable 1, Multimodal damping 2, Experimental investigation 3

1. INTRODUCTION

In recent years, high-order VIV of the stay cable (up to the 30^{th}-50^{th} order) has been frequently observed on some cable-stayed bridges. For instance, Ge et al. (2019). found that stay cables on the Sutong Yangtze River Bridge experienced the high-order VIVs with a frequency ranging from 9.5-10 Hz (about the 35^{th} mode) under the wind speed of 4-8 m/s. Other researchers also observed high-order and multi-mode VIV on the cables of the Sutong Bridge (Di, et al., 2021; Wang, et al., 2022;). Kim al. (2022) reported that large amplitude VIV of the Cables L36 and R36 on a cable-stayed bridge opened in April 2019 in South Korea was observed with a frequency of 20 Hz (about the 65^{th} mode) and an amplitude of 50 m/s^2, even if the hybrid countermeasures of dampers and helical fillets were adopted on these cables. People used to adopt a single VD to mitigate the RWIV of stay cable, and the parameters of the single VD are designed according to the low-order modes. But this kind of VD will have poor performance to reduce the high-order VIV. Consequently, a new type of countermeasures should be found to simultaneously reduce the low-order RWIV and high-order VIV.

2. DESIGN AND MANUFACTURE OF PECDS WITH ADJUSTABLE DAMPING

In order to conveniently adjust the damping coefficient of the damper in the tests, a plate eddy current damper (PECD) was specially designed and manufactured, shown as Fig. 1. The PECD, which can export damping force, is a typical VD. If an additional mass is installed near the PECD, the functions of a VID can be totally implemented. The damping force of a typical VD and a VID can be determined by Eq. (1) and Eq. (2) respectively.

$$F_d = c_d \frac{du}{dt} \tag{1}$$

$$F_d = c_d \frac{du}{dt} + m_d \frac{d^2u}{dt^2} \tag{2}$$

where, c_d is the damping coefficient of the PECD; u is the relative displacement between the conductor plate and the permanent magnets; t is the time; m_d is the attached mass on the test stay cable near the PECD.

Fig. 2 shows the variation of the damping coefficient cd of the PECD with the size of the air gap obtained by numerical simulations, together with the results obtained by the test on the PECD prototype. It can be found that the damping coefficient decreases sharply with the air gap when the air gap increases from 2 mm to 12 mm. It appears that the results of the damping coefficients obtained by the numerical simulations and the tests on the prototype are in good agreement.

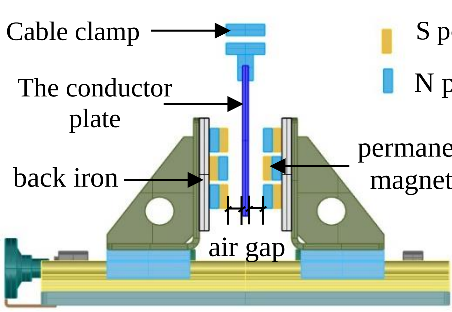


Figure 1. schematic diagram of the PECD

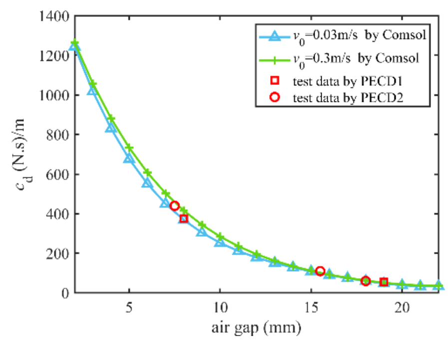
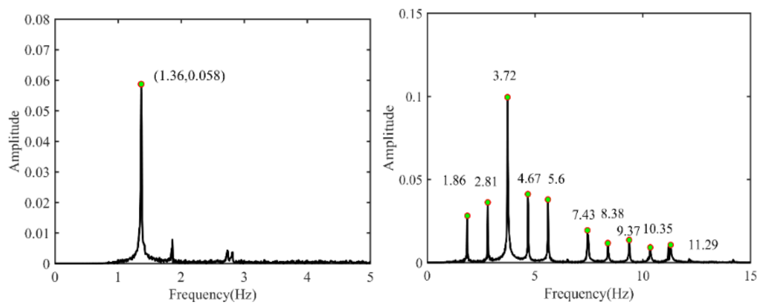


Figure 2. Variation of the damping coefficient with the air gap

3. TEST STAY CABLE

The detailed parameters of the test stay cable are introduced as following: the length of this stay cable is l=24.2 m, the mass per unit length is m=11.01 kg/m, the inclined angle θ is 14.2°, the area of cross section is A_c=1.347 cm^2, and the elastic modulus E is 1.9×1011 N/m^2. The dynamic characteristics of this stay cable was measured by adding artificial excitations at the locations of l/2 and l/7, and the spectrum analysis from the free decay time histories are presented in Fig. 3. According to the cable parameters listed in Tab.1, the dimensionless sag λ^2=11.360, which also indicates the influence of the sag on the natural frequency of f_1 would not be ignored.

The natural frequencies of this sagged stay cable can also be obtained by numerical simulations (Wang et al., 2022), and the results of the first thirty modes are listed in Table 1. It can be found from Table 1 that the natural frequency f_1 obtained from numerical simulations is 1.37 Hz, which agrees well with the measured value (1.36 Hz) presented in Fig. 3(a). Moreover, the natural frequencies of the 2^{nd}~6^{th} and 8^{th}~12^{nd} modes listed in Table 1 obtained from numerical simulations also agree well with those measured on the test stay cable, as shown in Fig. 3(b). Hence, the tension T of the test stay cable computed by the second frequency is T=24.5 kN.



(a) 1/2*l* (b) 1/7*l*

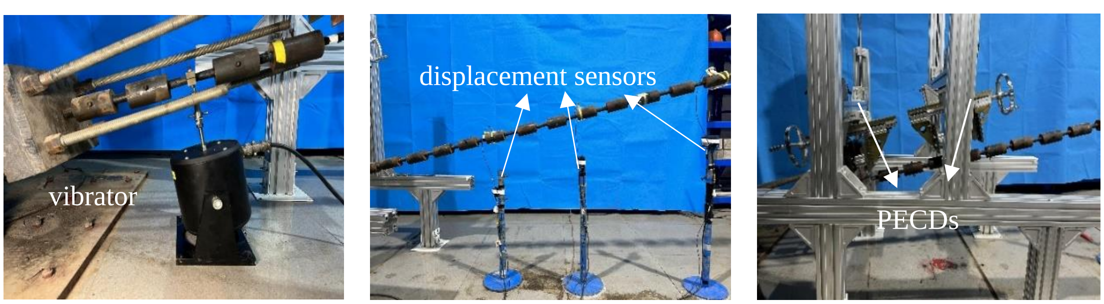
Figure 3. The spectrum analysis of the test cable:

Table 1. Natural frequencies of the first 25 modes of the cable obtained from numerical simulations

Modes	Natural frequencies (Hz)				
No. 1~5	1.37	1.95	2.94	3.90	4.88
No. 6~10	5.85	6.82	7.80	8.77	9.75
No. 11~15	10.72	11.69	12.67	13.64	14.62
No. 16~20	15.59	16.57	17.54	18.52	19.49
No. 21~25	20.46	21.44	22.41	23.39	24.36

4. OUTLINE OF THE TESTS FOR MULTIMODAL DAMPING RATIOS OF CABLE-DAMPER SYSTEM

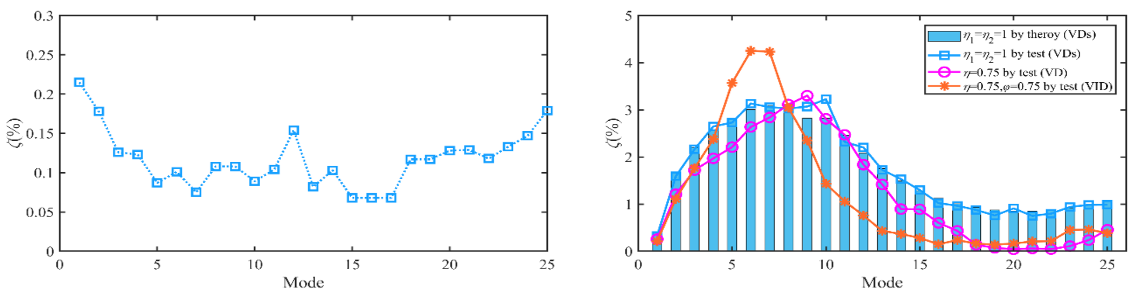
The vibrations of the modes of the stay cable listed in Table 1 were excited one by one by a DH40200 vibrator, as shown in Fig. 4(a). For each mode, the excitation frequency was tuned near the target frequency of the stay cable to ensure that only the targe mode was purely excited. After the vibration reached a steady amplitude, the vibrator was suddenly stopped and left the stay cable to keep a free decay vibration. The modal damping ratios were identified by using free vibration decay method. The in-plane displacement of the stay cable was recorded by laser displacement sensors with a sampling frequency of 200 Hz. Three laser displacement sensors were respectively arranged at the points of *l*/11, *l*/9 and *l*/7 from the lower end, as indicated in Fig. 4(b). The PECDs installed on the cable are shown in Fig. 4(c).



(a) Vibrator (b) Laser displacement sensor (c) The PECDs

Figure 4. Tested photos of cable-PECDs system vibration mitigation

There are four test cases in total corresponding to the cable itself, the single VD, the single VID, and the VDs. Fig. 5(a) shows the inherent damping of the cable and it can be seen that the inherent damping ratios are within the range from 0.068% to 0.22% and gradually decreases with the increase of modal order. Fig. 5(b) shows the variations of the damping ratio provided by the single VD, the single VID, and the VDs with the modal order, two VDs can significantly improve the damping ratio of nodes and nearby modes of the cable-VD/VID system. Note that in Fig. 5(b), the dimensionless damping coefficient is $\eta = \frac{c_d}{\sqrt{Tm}}$, and the dimensionless inertial mass is $\varphi = \frac{m_d}{ml}$.



(a) only cable (b) the cable with dampers

Figure 5. The damping ratio of the test cable with the modal order

5. CONCLUSIONS

In this study, the mechanical properties of PECD are analyzed in detail, and the damping of the cable-damper system is studied by complex mode analysis and experiment. The main conclusions are summarized as follows: the modal damping ratio of the cable itself decreases with the increase of modal order. Compared with VD, the increase of inertia will indeed reduce the damping effect of some higher-order modes. Two VDs can significantly improve the damping ratio of nodes and nearby modes of the cable-VD system. The cable-VDs system has better control effect on multi-mode vibration reduction.

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