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Flow characteristics of vortex-induced vibration of cable model under passive-suction-jet control

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SUMMARY:
The control effect and flow characteristics of a passive-suction-jet control scheme on the vortex-induced vibration (VIV) of a stay-cable model were experimentally investigated in this study. The vibration responses and flow characteristics of an elastically mounted rigid cable model under passive-suction-jet control were measured at damping ratios (ξ) of 0.11%–0.23% and Reynolds numbers (*Re*) of 12700–29200. The control scheme was realized using specially designed pipes that could spontaneously produce jet flow from the holes on the leeward surface of the pipes. The results of the vibration responses show that the passive-suction-jet control was effective in suppressing cable VIV. The control mechanism of the pipe was also explored in terms of swirling strength distributions, streamlines, and velocity profiles in the wake field. The jet flow from the pipes was unsteady and formed periodic small-scale vortices at ξ=0.11%. At ξ=0.17%, the jet flow was a steady flow and could suppress VIV more effectively.

Keywords: vortex-induced vibration, stay-cable model, passive-suction-jet control

1. INTRODUCTION

The cables of long-span bridges are long-slender structures which are characterized by low damping and stiffness. Therefore, they are prone to oscillation under wind action and suffer from vortex-induced vibration (VIV). In recent decades, the VIVs of cables have been monitored frequently in bridges (Main and Jones, 1999; Chen et al., 2019). Although the amplitude of the VIV is limited, the excited wind velocity is low; thus, the occurrence of VIV is frequent. Therefore, vibration control of cables is important in engineering practice and has been extensively studied. Chen et al. (2015) proposed a passive-suction-jet pipe to control the flow fields and VIV of circular cylinders. The pipe is specially designed to allow air to blow into the pipe through the holes on the windward surface and blow out spontaneously from the leeward surface. The jet blown out from the holes on the leeward surface alters the alternative vortex shedding process. Previous studies have primarily focused on the mechanism of passive-suction-jet control on a stationary circular cylinder. However, rare researchers have investigated the VIV suppression and control mechanism of the pipes on a circular cylinder. In this study, a wind tunnel experiment was conducted to investigate the flow characteristics and effectiveness of passive-suction-jet control on the VIV of an elastically mounted rigid cable segment model at various damping ratios to reveal the flow control mechanism from a fluid perspective.

2. MODEL DESCRIPTION AND EXPERIMENTAL SETUP

The experiments were conducted in a wind tunnel. A rigid circular cylinder with a diameter (D_0) of 0.08 m and length of 0.768 m was used as the cable segment model and fixed on a steel rod with a diameter of 10 mm. The steel rod was supported by four springs; therefore, a spring-mass system was established, and the cable model could vibrate freely in the vertical direction. A passive suction-jet control scheme was implemented using a specially made hollow pipe, as shown in Fig. 1. The pipe had an inner diameter (D_0) of 0.08 m and can be installed on the outer surface of the cable model. Twenty-four square holes were placed on the outer shells of the pipes. The height of the pipe and thickness of the channel inside the pipe are 0.8 D_0 and 0.05 D_0, respectively. The shell thickness was 1 mm; therefore, the outer diameter of the pipes (D) was 0.092 m. Twelve pipes were installed on the outer surface and they fully covered the surface of the model in the controlled case. In the uncontrolled case, the suction-jet holes were sealed with the tape and the airflow inside the pipes was blocked. Therefore, the characteristic size (D) of the test models in the two cases was 92.0 mm. The experimental details are listed in Table 1.

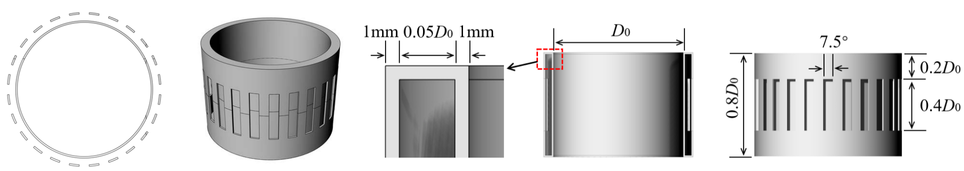


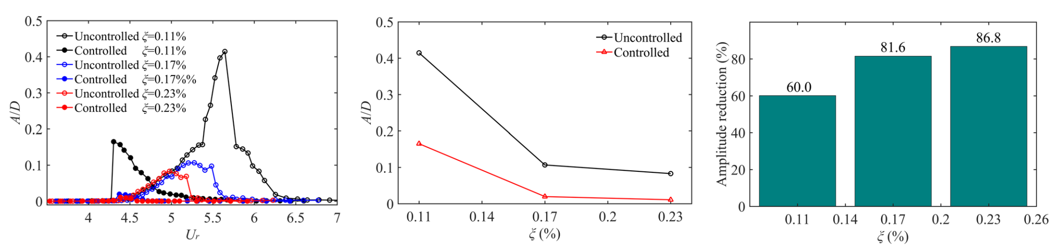
Figure 1. Schematic and geometry of passive-suction-jet pipes.

Table 1. Parameters of cable model and experiment.

Parameters	Symbol	Unit	Value	
			Uncontrolled case	Controlled case
Mass ratio	m^*	1	389	390
Natural frequency	f_0	Hz	7.94	7.94
Damping ratio	ξ	%	0.11, 0.17, 0.23	0.11, 0.17, 0.23
Scruton number	$Sc(=0.5\pi m^*\xi)$	1	0.672, 1.039, 1.405	0.674, 1.041, 1.777
Wind velocity	V	m/s	2.0–4.6	2.0–4.6
Turbulent intensity	I_u	%	<0.4	<0.4

3. VIBRATION RESPONSE

The vibration response shows that the increase in the damping ratio can reduce the vibration amplitude of a cable model for both uncontrolled and controlled cases. The passive-suction-jet pipe can effectively mitigate the vibration, especially at $\xi \geq 0.17\%$.



(a) (b) (c)

Figure 2. Vibration response for cable model with and without control: (a) amplitude of displacement versus reduced velocity, (b) maximum amplitude, (c) amplitude reduction.

4. FLOW STRUCTURE

The wake fields of the cable model were identified using a particle image velocimetry system. The flow fields at eight moments in one vibration cycle were recognized using the phase-average method. The eight phases and the corresponding displacements are depicted in Fig. 3.

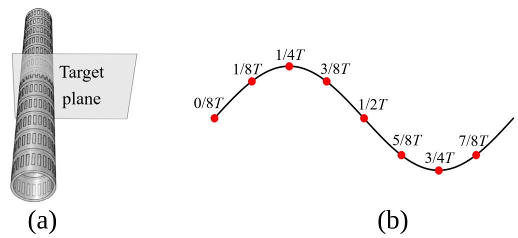


Figure 3. Target plane in PIV measurement (a) and displacement schematic at eight moments in one cycle (b).

Figure 4 shows the evolution of the phase-averaged swirling strength in the wake of the model at ξ = 0.11%. An alternative vortex shedding process was observed and two new vortices shed into the wake during one cycle. Thus, the vortex shedding mode was a typical 2S mode, the formation of the wake vortex causes a periodic vortex force in the model. Under the control of passive-suction-jet pipe at ξ = 0.11%, The vortices were formed at X=0.89D and shed near X=1.55D, which were larger than those in the uncontrolled case at ξ = 0.11%, as shown in Fig. 5. Figures 6 and 7 show swirling strength distribution in the near wake of the model for the controlled case at ξ = 0.11% and 0.17%. A series of small-scale vortices were formed near the holes of the pipe. At 0T, both clockwise vortices and anticlockwise vortices existed. At 1/8T, the anticlockwise vortices were strengthened. When the model reached the maximum position, the anticlockwise vortices started to merge. At 5/8T, these small-scale anticlockwise vortices merged into one vortex (named SA1) and shed into the wake of the model. As the vortex SA1 moved downstream at 3/4T and 7/8T, the small-scale clockwise vortices started to merge and repeated this process. The periodic jet flow formed an alternative vortex shedding process in the near wake of the model eventually. These combined small-scale shedding vortices would involve into the Karman vortices that shed from both sides of the model. This illustrated that the jet flow was an unsteady flow at a low damping ratio. Although the jet flow was unsteady, the Karman vortices were pushed downstream. Thus, the vortex induced forces exerted on the model were reduced. At ξ = 0.17%, the small-scale vortices can be also seen in the region near the holes of the pipe, while the merging of these vortices was hard to be observed. And no significant changes in these vortices can be seen during one vibration cycle, which indicates that the jet flow blowing from the holes was steady flow. The steady jet flow could significantly reduce the fluctuating aerodynamic force on the rear surface of the model and suppress the VIV.

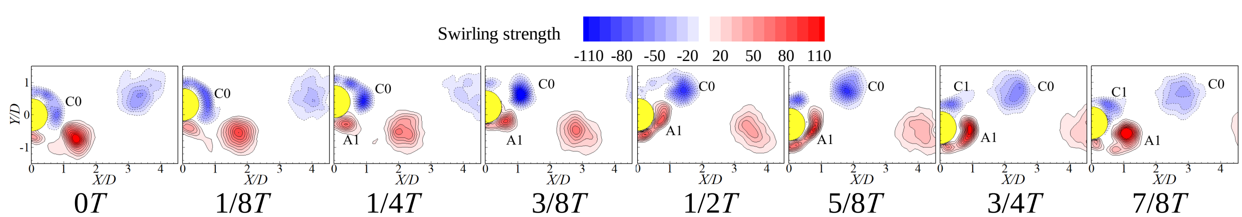


Figure 4. Evolution of swirling strength for the uncontrolled case at ξ = 0.11% and U_r = 5.6.

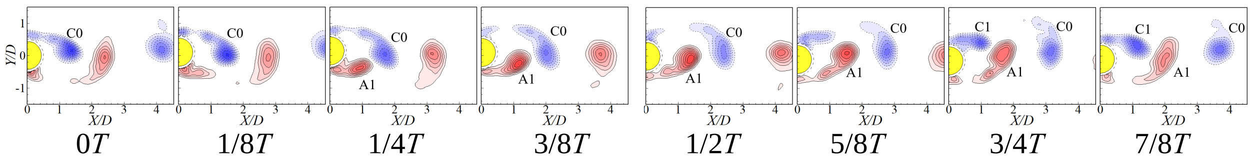


Figure 5. Evolution of swirling strength for the controlled case at ξ = 0.11% and U_r = 4.3.

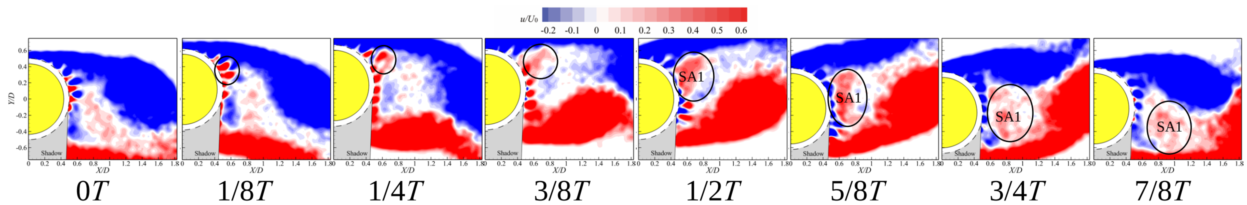


Figure 6. Swirling strength in the near wake for the controlled case at ξ = 0.11% and U_r = 4.3.

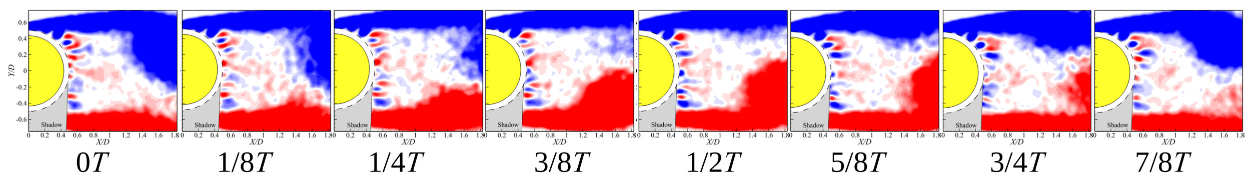


Figure 7. Swirling strength in the near wake for the controlled case at ξ = 0.17% and U_r = 4.4.

5. CONCLUSIONS

A wind tunnel experiment was conducted on an elastically mounted rigid cable model to investigate the VIV characteristics and suppression. For a cable at a small damping ratio, the increase in the damping caused a significant reduction in VIV, while the influence of the change in the damping ratio on the VIV response was weakened at high damping ratios. Under the control of the passive-suction-jet pipes, the initial excitation branch in the VIV response was eliminated completely. The VIV response was effectively suppressed, particularly at high damping ratios. The vortex shedding mode was the 2S mode for all cases in this study. Under the control of the pipes, the vortex formation region moved further downstream. The swirling strength distribution in the near wake indicated that the jet flow was diverse at different damping ratios. At a small damping ratio, the jet flow blown from the holes on the leeward surface was an unsteady flow and formed periodic small-scale vortices in the near wake. For the cable model with a high damping ratio, the jet flow was a steady flow and acted as a virtual shape and pushed the vortex formation region further downstream. The steady jet flow reduced the vortex forces exerted on the model and suppressed the cable VIV more effectively.

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