An experimental investigation on vortex induced vibration of a flexible inclined cable under a shear flow

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A B S T R A C T

In the present study, an experimental investigation was performed to characterize the vortex induced vibration (VIV) of a flexible cable in an oncoming shear flow. The VIV tests were conducted in a wind tunnel with a flexible cable model. It was found that, under different oncoming velocity profiles, the cable model behaved in single-mode and multi-mode VIVs. The displacement amplitudes of the single mode VIVs were found to be larger than those of multi-mode VIVs, and the cross-flow (CF) response was larger than that of in-line (IL) direction for either the single mode or multi-mode VIVs. For a single mode vibration, the largest CF response occurs in the 1st mode VIV, and the motion trajectory of the 1st mode VIV was found to be an inclined figure of eight shape, while other single mode VIVs behaved in ellipse or straight line trajectories. For multi-mode VIVs, no stable vibration trajectories were found to exist since the vibration frequency bands covered two or more vibration modes. The vortex-shedding frequencies in the wake behind the inclined cable were also characterized in the present study. The shedding frequencies of the wake vortices were found to coincide well with the vibration modes: for a single mode VIV, they were close to the dominant vibration mode; for a multi-mode VIV, they could also cover the appearing vibration modes.

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1. Introduction

In recent years, more and more long-span bridges, such as suspension or cable-stayed bridges have been widely constructed worldwide due to their superior structural performance and elegant appearance. As we all know that, a uniform flow induces a single vortex shedding frequency, in contrast, non-uniform flows can potentially trigger responses with multiple narrow-band components since the vortex shedding frequency depends on the oncoming flow velocity and more than one modal frequency will be excited. All these long-span bridges are built in the atmospheric boundary layer where the velocity increases with the height. The key components of these long-span bridges, stayed cables, easily behave in multi-mode VIVs while in this non-uniform flow, i.e., the velocity profile in the atmospheric boundary layer (Main and Jones, 1999; Matsumoto et al., 2003; Zuo et al., 2008; Zuo and Jones, 2010; Chen et al., 2011, 2013). Zuo et al. (2008) and Zuo and Jones (2010) performed full-scale measurement investigations on the Fred Hartman Bridge in Houston (Texas, USA) and observed VIVs of cables with sixth and seventh modes or with fifth and sixth modes, respectively. Chen et al. (2011) observed the occurrence of higher multi-mode (nearly 20th) VIVs of the inclined cables in a cable-stayed bridge in China. Under a large velocity profile, when the velocity differences between the upper and lower ends of an...
inclined cable are large enough to excite two and more vibration modes, the inclined cables will behave in a multi-mode VIVs. Furthermore, Chen et al. (2013) indicated that the inclined cables with a length of 100 m would behave in mono-mode and multi-mode VIVs under different velocity profiles based on numerical simulations.

Being comparable to inclined cables, the VIVs of oceanic risers also happen more frequently. Both field and laboratory tests on long flexible risers in shear flows revealed the multiple frequencies of response (e.g., Lie and Kaasen, 2006; Trim et al., 2005; Vandiver et al., 2009). Lie and Kaasen (2006) carried out model analysis of measurement from a large-scale VIV testing model in linearly shear flow by using a riser model with a length of 90 m and diameter of 3 cm. Under a large velocity profile, the riser presented broad-banded response and no occurrences of single-mode (lock-in) were ever seen. Trim et al. (2005) performed the experimental investigation of VIV of long marine risers. It was found that the cross flow (CF) displacement is higher than the in line (IL) displacement for all velocities and the IL modes are approximately twice as much as that of the CF modes. At a low flow velocity, there was a relatively narrow band of dominant modes in all cases and the band broadens out at higher flow velocity, which is most evident for the CF response. Vandiver et al. (2009) conducted VIV experiments on a quite long (152.4 m) flexible cylinder in the ocean. The traveling wave VIV was dominant at high mode numbers with strong higher harmonic components and stable figures of eight trajectories.

Moreover, Mathelin and de Langre (2005) and Violette et al. (2007) investigated VIVs of long risers under ocean shear flows by using a wake oscillator model. The risers showed multi-mode or mono-mode responses under different shear flows. Their results provided a precious estimation of the vibration amplitudes along the risers. As the span of the bridge increases, the wind profile between two ends of a stayed cable becomes remarkable with the length of the cable increasing dramatically. The wind speed is normally increasing with height; the cable may experience higher shedding frequency at the higher end and such flow profile may excite more than one natural frequency of the cable. Therefore, it is essential to investigate the VIV of an inclined cable under different wind velocity profiles. Computational fluid dynamics (CFD) numerical simulations were also used to study the VIV characteristics of long flexible cylinders. By means of direct numerical simulations, Newman and Karniadakis (1997) and Evangelinos and Karniadakis (1999) studied flow-induced vibrations of a flexible cable at Re=100 and Re=1000, respectively. The wake patterns were investigated in detail by combining the influence of the nature of the vibration (standing or traveling wave) on the flow structure development. However, the results were obtained in a uniform flow. Lucor et al. (2006) performed VIV studies of long flexible cylinders with aspect ratios larger than 500 in linear and exponential shear flows. Compared with each other, the bandwidth of large oscillation in an exponential shear flow was greater than that in a linear shear flow. Bourguet et al. (2011) investigated VIVs of a long flexible cylinder in a shear flow with an aspect ratio of 200 and at three different Reynolds numbers from 110 to 1100. As a multi-mode VIV, traveling waves were the main part of the flow structure between the two ends of the long cylinder and the standing wave was predominant near the ends, its contribution increasing with Reynolds number. The synchronization region which covered at least 30% of the cylinder length was often lying within the high-velocity zone. They also obtained that the in-line and cross-flow vibrations had a frequency ratio approximately equal to two. However, Huera-Huarte and Bearman (2009) conducted a test for showing the dynamic response of a vertical long flexible cylinder vibrating at low mode numbers. The results indicated that the dominant frequency of the in-line vibrations is the same with that of cross-flow vibrations due to the reason that the IL response frequency cannot lock on the 2nd mode even with added.

In the present paper, the VIVs of an inclined flexible cable model with a length of 6.08 m under different wind velocity profiles were performed to investigate the characteristics of the vibrations and the wake frequencies of the cable model. The structure of this paper is arranged as follows. In Section 2, the experimental setup for reproduction of VIV of the cable model is finished. In Sections 3 and 4, the characteristics of the VIV of the cable model are studied, including the characteristics of the cable vibrations and vortex shedding frequencies varying along the axial direction of the cable in the wake, followed by a section of conclusions derived from the present study.

2. Experiment setup

The experiments were performed in the Joint Laboratory of Wind Tunnel and Wave Flume located at Harbin Institute of Technology (in China) as shown in Fig. 1. The wind tunnel is a closed loop tunnel with two test sections. The dimension of the smaller test section is 4.0 m (width) × 3.0 m (height) with a length of 25 m, and that of the larger one is 6.0 m (width) × 3.6 m (height) with a length of 50 m. The wave trough is located under the larger section and separated by movable floors. The maximum wind speeds can be up to 50 m/s and 30 m/s for the small and large test sections, respectively.

2.1. Flexible cable model

The flexible cable model had a length L of 6.08 m, and the diameter D of cable is 0.042 m. The aspect ratio of cable in this study was about 144.7. The weight of the cable model was 0.467 kg/m. The experimental configurations were shown in Fig. 1(a), the lower and upper ends were 0.45 and 3.05 m above the floor of the wind tunnel, and the inclined angle of the flexible cable was 25.3° and the yaw angle was set as 0° in the testing.

The cable model was axially tensioned by two end plates with a tension of 850 N: the upper end fixed on the upper plate and the lower end fixed on the lower plate. Two ends of the cable model cannot move in the axial, CF and IL directions. The cross-section of the cable model is shown in Fig. 1(b) where the cable model had a 7.5 mm diameter steel stand core with multi-layer foam tapes attached to it. This skeleton structure was covered with a flexible PVC skin, providing an
external diameter of 0.042 m. It should be noted that the cable tension is undertaken by the steel stand core and no axial load is carried by the multi-layer foam tapes and the flexible PVC skin.

Four accelerometers (Brüel and Kjær 4507B) were employed to measure the cross-flow (CF) and in-line (IL) vibration responses on two positions which are 1.256 and 3.403 m away from the lower end along the axial direction of the cable model, respectively. Accelerometer 1 (i.e., 3.403 m location) and accelerometer 2 (i.e., 1.256 m location) were set to measure the CF vibrations, and accelerometer 3 (i.e., 3.403 m location) and accelerometer 4 (i.e., 1.256 m location) were used to measure the IL vibrations of the cable model. The sampling rate was 1000 Hz and the sampling time of each case was 60 s.

A hot-wire anemometry (DANTEC DYNAMICS) was used to measure the wake velocity and was placed in near wake of the cable model. The relative position of the hot-wire anemometry to the cable cross section is illustrated in Fig. 1(a). The sampling rate and time were set the same as that of the acceleration measurement system. The measurement positions of the hot-wire anemometry could be automatically moved from the lower end (0.22 m) to upper end (5.42 m) along the axial direction of the cable model as shown in Fig. 1(a). The interval space between two measurement positions was 100 mm.

Prior to the wind tunnel test, free vibration tests were conducted firstly to obtain the modal frequencies and damping ratios of the flexible cable as shown in Table 1.

It should be noted that the first two modal damping ratios were easily obtained from the free vibrational time histories; however, the other higher order modal damping ratios were difficult to be measured. Therefore, it is supposed that the modal damping ratios satisfy the Rayleigh proportion damping model as follows (Chopra, 2001):

\[ [C] = \alpha[M] + \beta[K] \]  

(1)

where \([C]\) is the Rayleigh proportion damping matrix, \([M]\) and \([K]\) are the mass and the stiffness matrices, respectively, and \(\alpha\) and \(\beta\) are the coefficients which can be determined by the first two modal frequencies and damping ratios. After determination of \(\alpha\) and \(\beta\), the other higher order modal damping ratios can be calculated from Eq. (1).

2.2. Velocity profile of the oncoming shear flow

The oncoming shear flow was produced by using spires which were arranged at the inlet of the test section. Fig. 2(a) shows the velocity profile measured in the tests when the mean wind speed at the height of the upper end of the test cable
model is about 5.0 m/s. The position of measured velocity profile is 1.0 m in front of the cable model. Under the height of 2.15 m, the measured velocity profile can be fitted well by using a power function $U(z) = U_b(z/z_b)^\alpha$, where $U_b$ is the wind speed at a reference height of $z_b$ and the index $\alpha$ is 0.12. Fig. 2(b) indicates the turbulence intensity profile. In the cable height range (0.45–3.05 m), the turbulence intensity slightly varies in a narrow range of 4.1–6.6%.

In order to determine the testing velocities which can induce the VIVs of different vibration modes; the mean wind speed increases from 0.7 to 7.5 m/s at the upper end height by an increasing velocity step of 0.1 m/s. At each mean wind speed, the measurement for the cable vibration was conducted. At last, eight velocities at the upper end height of the cable: 0.9, 1.8, 3.1, 3.6, 4.2, 5.4, 6.5 and 7.4 m/s were chosen to be analyzed.

In advance of eight velocity cases chosen, the flow velocity profile was determined by the spires; therefore, the flow profiles of eight cases were not measured and just the velocities at the heights of the upper and lower ends of the cable model were measured. In the present tests, the normalized velocity profiles of eight cases were supposed to be same.

### 3. Single mode VIV of cable model

#### 3.1. Vibration characteristics

When the upper end velocities are 0.9, 1.8, 3.1 and 4.2 m/s, which are named as case S1, case S2, case S3 and case S4, respectively, the flexible cable mainly behaves in a single mode vibration from 1st to 4th mode as shown in Fig. 3. Accelerometers 1 and 2 indicate the CF vibrations and accelerometers 3 and 4 indicate the IL vibrations. The frequency spectrum results indicate that the dominant frequencies are the same between the CF and IL vibrations. The present results are different with those reported by Bourguet et al. (2011). They obtained that the in-line and cross-flow vibrations had a frequency ratio approximately equal to two by using CFD numerical simulations. However, Huera-Huarte and Bearman (2009) conducted a test to show the dynamic response of a vertical long flexible cylinder vibrating at low mode numbers. The added mass is able to adjust the natural frequency and the shedding frequency to lock on each other. However, the natural frequency of the second mode is more than twice of the first mode (Huera-Huarte, 2006). The IL response frequency cannot lock on the 2nd mode even with the added mass; therefore, the IL is vibrating at the 1st mode. For the present tests, the CF 2nd modal frequency of 6.92 Hz is less than two times the value of the 1st mode (7.07 Hz as shown in Fig. 3(a)). The added mass is small and not able to tune the natural frequency as much as it can in the water.

For a single mode VIV of the flexible cable, the CF vibration amplitudes are larger than the IL vibration amplitudes. For lower-order single mode vibrations, i.e., the 1st and 2nd mode vibrations, the vibration amplitudes are steady and have no significant change in time. For the IL vibration of 1st mode VIV, the higher frequency components, i.e., 2nd and 3rd modal frequencies appear in the frequency spectrum as shown in Fig. 3(a). The results reported by Huera-Huarte and Bearman (2009) showed that a twice frequency component of the dominant frequency also appeared in the frequency spectrum with a small amplitude.

For higher-order single mode vibrations, i.e., the 3rd and 4th mode vibrations, the vibration amplitudes are unsteady and show a significant change in time whatever in the CF or IL vibrations. For the 4th mode VIV, there is not only a higher

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**Table 1**

<table>
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<th>Modal frequencies and damping ratios.</th>
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<td>Mode</td>
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<tr>
<td>IL</td>
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<td>Damping ratio (%)</td>
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**Fig. 2.** Velocity and turbulence intensity profiles: (a) velocity profile and (b) turbulence intensity profile.
frequency component, i.e., 5th modal frequency; but also lower frequency components, i.e., 1st, 2nd and 3rd modal frequencies in the frequency spectrum as shown in Fig. 3(d). It means as the mean wind speed increases, the velocity difference between two ends of the cable model also increases, as a result, other modal frequencies appear in the frequency spectrum when higher-order single mode VIVs occur. Moreover, for a turbulent oncoming flow with a turbulence intensity of about 5% as shown in Fig. 2(b), the model can also have buffeting response involving multiple modes due to the presence of turbulence when the vibration induced by vortex shedding is not so dominant as to render the modal components due to buffeting invisible in the spectrum. When the velocity differences continuously increase and the resultant vortex shedding frequency range can cover two or more modal frequencies, then the multi-mode VIVs will occur.

Fig. 3. Cable vibration responses at different test cases: (a) case S1, (b) case S2, (c) case S3, and (d) case S4.
3.2. Motion trajectory

For the VIV of a flexible cable, the high frequency components often exist in the vibration, such as in the IL vibration of Fig. 3(a). If the IL vibration frequency is the same or very close to the CF oscillation frequency, the motion trajectory will be a linear line or an ellipse which are decided by the phase differences between CF and IL vibrations. If the IL vibration frequency is twice the CF oscillation frequency, the motion trajectory will be a figure of eight shape.

The motion trajectory of the cable vibration at the wind speed of 0.9 m/s (i.e., case S1) is shown in Fig. 4(a) and it indicates that the motion trajectories at two accelerometer locations of the cable are different and they are inclined irregular figures of eight shape which indicates that there is a 2nd modal frequency component in the IL vibration. When the velocities increase to 1.8 and 3.1 m/s (i.e., cases S2 and S3), the motion trajectories are ellipses as shown in Fig. 4(b) and (c). According to the comparison of the time histories of CF and IL vibrations, the change of the phase differences between CF
and IL vibrations will result in different ellipses. For case S2, the phase differences between CF and IL vibrations at locations of accelerometers 1 and 2 are 167.23 and 171.74°, respectively; for case S3, the phase differences between CF and IL vibrations at locations of accelerometers 1 and 2 are 153.45° and 150.62°, respectively. The phase difference is closer to 0 or 180°, the ellipse is more prolate.

When the velocity is 4.2 m/s (i.e., case S4), the vibration time histories in CF or IL directions are irregular and the motion trajectories are unstable figures between the straight lines and the ellipses, however their trend is to be more like inclined lines as shown in Fig. 4(d).

3.3. Frequency spectra characteristics of wake fluctuating velocity

The VIVs of the flexible cable were induced by the unsteady aerodynamic forces and the vortex shedding frequencies were the crucial roles to trigger the VIVs. As limited by the installation of the hot wire sensor, the wake frequency measurement range was 220–5420 mm from the lower end along the axial direction. The wake frequencies along the axial direction at four different cases are shown in Fig. 5. Meantime, according to the oncoming mean wind speed, the wake frequencies (i.e., the vortex shedding frequencies) can be estimated according to the oncoming mean wind speed, the Strouhal number and the cable diameter. The turbulence in the free-stream will influence the flow transition and change the effective Reynolds number. However, in the present test, the turbulence level was low (the turbulence intensity at most parts of the cable model are less than 5%). Furthermore, the maximum Reynolds number (case M4) was about $2.1 \times 10^4$, which was much less than the transition Reynolds number (about $1.5 \times 3.5 \times 10^5$). Therefore, the influence of the turbulence in the free-stream to the effective Reynolds number should be small and was neglected in the present testing.

As the Reynolds number changes with the height at different velocity profiles, the Strouhal number $St(z)$ is calculated using the following formula (Norberg, 2003):

$$\begin{align*}
St(z) & = 0.1853 + 0.0261 \times \exp \left( -0.9 \times L_R^{2.3} \right) \\
L_R & = \log \left( \frac{Re(z)}{1.6 \times 10^3} \right) \\
Re(z) & = \frac{U_0(z)D(z)}{\nu}
\end{align*}$$

where $D(z)$ is the cable diameter at the height of $z$ (in fact, it is constant for most cables), $Re(z)$ is the Reynolds number at the height of $z$, $\nu$ is the coefficient of kinematic viscosity and $U_0(z)$ is the oncoming velocity at the height of $z$.  

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The vortex-shedding frequency \( f_s(z) \) of a circular cylinder can be expressed as follows:

\[
f_s(z) = St(z) \frac{U_0(z)}{D(z)}
\]  

(3)

According to Eqs. (2) and (3), the estimated wake frequencies along the axial direction can be calculated as shown in Fig. 5 for four test cases. As shown in Fig. 5(a), for the cases S1 and S2, the estimated vortex shedding frequencies are not equal to but close to the measured wake frequencies which are nearly completely locked in at 1st and 2nd modal frequencies, respectively. Almost no other wake frequency components act on the cable model; therefore, the vibration histories were very steady as shown in Fig. 3(a) and (b).

As shown in Fig. 5(b), in the measurement range of 1000–5420 mm, the measured wake frequencies are close to the estimated vortex shedding frequencies at the cases S3 and S4. The cable vibration is small and cannot completely lock in the wake frequencies to the vibration frequencies: the wake frequencies are close to the vibration frequencies in the measurement range of 1000–3000 mm and the wake frequencies slowly increase with the height in the measurement range of 3000–5420 mm. Because other wake frequencies act on the cable model, the vibration histories are unsteady although they are single mode dominated VIVs as shown in Fig. 3(c) and (d); meanwhile, the vibration amplitudes are smaller than those of case S1 and case S2. In the measurement range of 220–1000 mm, the measured wake frequencies are larger than the estimated vortex shedding frequencies. One reason may be that the turbulence intensity in this range is relatively larger than that in the range 1000–5420 mm and may take more buffeting response invisible in the spectrum; however, the main reason should be that the wind speed increases when the flow moves cross the lower end plate as shown in Fig. 1(a).

4. Multi-mode VIV of cable model

4.1. Vibration characteristics

When the velocities at the upper end height are 3.6, 5.4, 6.5 and 7.4 m/s, which are named as case M1, case M2, case M3 and case M4, respectively, the flexible cable mainly behaves in multi-mode vibrations as shown in Fig. 6. For each case, i.e., case M1–M4, the tests were performed for the cable vibrations 29 consecutive times. Fig. 6 only shows the results of one test and the amplitudes (RMS) of all 29 tests are then analyzed as shown in Fig. 7. Combining Figs. 6 and 7, it is found that, although the amplitudes of multi-mode VIVs for these four cases are unsteady in a short period (i.e., one test), they are
relatively steady in a long period (i.e., 29 tests). Comparing Figs. 6 with 3, the displacement amplitudes of multi-mode VIVs are less than the amplitudes of single mode VIVs (particularly cases S1 and S2), for either the CF or IL vibrations. However, the acceleration amplitudes of multi-mode VIVs are the same level with those of the single mode VIVs as shown in Fig. 7(b). The high frequency vibration with smaller displacement amplitude may not bring devastating damages to the cables, however, it is suggested that the high frequency VIVs of cables may induce potential unsafety to the bridges; therefore, the multi-modes VIVs should attract more attention by the researchers and the bridge designs.

Similar with the single mode VIVs, the CF vibrations are larger than the IL vibrations for the multi-mode VIVs. For the IL vibrations, several lower modal frequency components with larger amplitudes were included in the spectra for all four cases; however, for the CF vibrations, the corresponding amplitudes of these lower modal frequencies are very small in the frequency spectra.

For a multi-mode VIV, at least two modal frequencies exist in the vibrational response. For further investigating the change of each modal frequency with time, the time-frequency analysis of the vibration response was then conducted.

Fig. 6. Cable vibration responses at various cases under high wind velocity: (a) case M1, (b) case M2, (c) case M3, and (d) case M4.
The time frequency analysis is obtained by using a wavelet transform. The wavelet used here is Gabor wavelet which is a Gaussian modulated by a complex exponential as follows:

$$\psi(t) = \frac{1}{(\sigma^2 \pi)^{1/4}} \exp \left(-\frac{t^2}{2\sigma^2} + 2\pi j f_0 t \right)$$

(4)

where $f_0$ is the central frequency and $\sigma$ determines the frequency bandwidth, in the present analysis, the central frequency and the frequency bandwidth are chosen 5 and 10 Hz, respectively.

Fig. 8 shows the time-frequency analysis for the CF acceleration signals of accelerometer 1. As mentioned above, the case M1 is a two modes VIV from the frequency spectrum as shown in Fig. 6(a). However, the time-frequency analysis shows that the 3rd modal frequency component is much smaller than the 4th modal frequency component. The 4th modal frequency is dominant in the time history and the 3rd modal frequency component only appears at some limited moments. For case M2,
it is a typical two modes VIV as shown in Fig. 6(b), two modal frequency components, i.e., the 5th and 6th modal frequency components alternately appear in the time sequence. For case M3, as a two modes VIV, the 6th modal frequency component are stronger and more dominant than the 7th one as shown in Fig. 6(c).

For case M4, it is a three modes VIV as shown in Fig. 6(d), however two modes: i.e., the 7th and 8th modes are dominant in the time history and the 6th modal frequency component only appears at some limited moments. Some other frequency components between the 7th and 8th modal frequencies also exist in the time sequence.

4.2. Motion trajectory

As multi-mode VIVs, the CF and IL vibrations have several modal frequencies which result in no stable phase differences of the vibrations between two directions; therefore, the cable vibrations had no stable motion trajectories as shown in Fig. 9. From these four test cases, the motion trajectories are close to straight lines which indicate that the most dominant frequencies of CF and IL should be the same. It can be validated from the frequency spectra of CF and IL vibrations as shown in Fig. 6. It should be noted, as shown in Fig. 6(a), there is a very small peak at the position of twice the dominant frequency in the IL vibration. The amplitude of this frequency component is very small; therefore, a figure of eight shape does not appear in the trajectory as shown in Fig. 9(a).

4.3. Frequency spectra characteristics of wake fluctuating velocity

Vortex shedding frequencies in the wake of the cable model at different velocity profiles (i.e., cases M1–M4) are shown in Fig. 10. As mentioned above, the turbulence intensity is relatively larger in the measurement range of 220–1000 mm which may take more buffeting response invisible in the spectrum and meantime the wind speed increases when the flow moves across the lower end plate; therefore, the measured wake frequencies are unsteady and larger than the estimated wake frequencies in this range for all four test cases.

In the measurement range of 1000–5420 mm, the estimated wake frequencies can better capture the measured wake frequencies. As multi-mode VIVs, the cable vibrations cannot lock in the wake frequencies and the wake frequencies slowly increase with the height for all four test cases.

For two-modes VIVs, i.e., the cases M1–M3, the wake frequencies are mainly located nearby two neighboring modal frequencies which are the dominant frequencies in the frequency spectra. For the case M1, the wake frequencies are more close to the 4th modal frequency; for the case M2, most of the wake frequency points are close to the 5th modal frequency; and for the case M3, most of the wake frequency points are close to the 6th modal frequency. Therefore, for these three cases, the most dominant frequencies should be the 4th, 5th and 6th modal frequencies, respectively, which can be validated from the results in Fig. 6(a–c) and Fig. 8(a–c). However, for the case M2, the frequency spectra of the accelerometers 2 and 4 show that the dominant frequency is the 6th modal frequency rather than the 5th modal frequency. The reason is that the location of the accelerometers 2 and 4 is 1.256 m from the lower end of the cable model. This location is very close to one of the 5th mode nodes (i.e., 1.216 m) from the lower end. The vibration amplitude at the location of a wave node: i.e., 1.216 m, is zero for a 5th mode vibration. At the location of 1.256 m, the measured vibration amplitudes by the accelerometers 2 and 4 are only $0.113$ times of the 5th mode vibration amplitude; therefore, the corresponding amplitude of this modal frequency is very small as shown in Fig. 6(b).

For a three-modes VIV, i.e., the case M4, the wake frequencies are between the 6th, 7th and 8th modal frequencies. The wake frequencies of most of the points are close to the 7th modal frequency; therefore, the vibration time histories exhibit more characteristics of the 7th mode as shown in the Fig. 6(d) where the 7th modal frequency is the most dominant frequency component.

According to the velocities between the two ends, the vortex shedding frequencies between the two ends can be calculated combining Eqs. (2) and (3) at the different velocity profiles. Fig. 11 shows the estimated vortex shedding frequencies between the two ends and the dominant frequencies of cable vibration at the different velocity profiles.
It is found that the cable vibration frequencies of the analyzed eight test cases are all in the range of the estimated vortex shedding frequencies between the two ends of the cable model. According to the above analysis, the VIV cable modes and frequency range can be predicted by using Eqs. (2) and (3) when the velocity profile is given.

Fig. 8. Time–frequency analysis for the CF acceleration signals of accelerometer 1: (a) case M1, (b) case M2, (c) case M3, and (d) case M4.
Fig. 9. Motion trajectories of the cable model at different test cases: (a) case M1, (b) case M2, (c) case M3, and (d) case M4.

Fig. 10. Vortex shedding frequencies in the wake at different velocity profiles.
5. Discussions

Long flexible cables of large span bridges are located in the atmospheric boundary layer and the VIVs of long flexible cables will occur frequently. As a long stayed-flexible cable (such as 100 m or longer), multi-mode VIVs are inevitable according to the velocity differences between the two ends of the stayed-cable. In the present study, even if the length of the stayed-cable is only 6.08 m, the multi-mode VIVs are also observed in the tests although the diameter of the test cable model is about one third of the actual stayed-cables. For an actual stayed cable which has a smaller fundamental natural frequency (less than 1 Hz), the velocity difference between the two ends will be significantly larger, resulting in a large excitation range which may excite more than one natural frequency. Therefore, we have reason to believe that the multi-mode VIVs are normal and frequent vibrations of the stayed-cables. Moreover, the vibration modes of multi-mode VIVs of the stayed-cable can be predicted if we know the velocity profiles based on the presented study. The velocity profiles can be preliminarily determined by the mean wind speed at the reference height near the stayed-cables and the terrain type where the stayed-cables are located.

As we know that the frequencies of drag forces are twice those of lift forces, the IL vibration frequencies are often twice the CF vibration frequencies. As a long flexible cable of an actual cable-stayed bridge, high modal frequencies are the multiple of the fundamental natural frequency; so the IL vibration modes will be incidental to twice the CF vibration modes. In the present paper, high modal frequencies are incompletely the multiple of the fundamental natural frequency. Therefore, the 2nd mode vibration in the IL direction and the stable figure of eight motion trajectory only appear for the 1st mode VIV. For other single mode or multi-mode VIVs, the dominant frequencies of IL vibrations are the same with those of CF vibrations, so the motion trajectories are an inclined ellipse or straight line.

In the present tests, the accelerometers are installed at only two positions to measure the cable vibration. It should be noted that the obtained relative modal participation is influenced by the location of the accelerometers. As mentioned above, for case M2, the lower set of accelerometers cannot pick up a large fifth-mode component, since the accelerometers are close to a nodal point of the 5th mode as shown in Fig. 6(b). However, more installed accelerometers and their signal acquisition cables may influence the wake flow and will take errors to analyze the wake frequencies.

6. Conclusions

In the present study, an experimental investigation was conducted to investigate the characteristics of VIVs of a flexible cable model under different velocity profiles. Some conclusions were obtained from this study as follows:

Different velocity profiles, i.e. velocity differences between the two ends of the flexible cable model were the key role to excite the cable VIV types: single mode or multi-mode. The occurrence of multi-mode needs a threshold difference of vortex shedding frequencies induced by the profile velocity between the two ends and this threshold should at least cover two modal frequencies.

The displacement vibration amplitudes of the multi-modes VIVs are always smaller compared with the single mode VIVs; however, the multi-modes VIVs have a same level of acceleration amplitudes with the single mode VIVs. For a multi-mode VIV, the dominant modal frequency components alternately appear in the time sequence and are interfered with each other. The most dominant mode of the response is the one which has more locations of wake frequency close to its modal frequency.

The estimated wake frequencies are close to the measured wake frequencies if the wake frequencies are not locked in to the cable vibration. The wake frequencies can be locked in to the vibration frequency only for a single mode VIV and if the cable vibration is large enough.
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