**Aerodynamic Force Time-frequency Evolution Characteristics of the Streamlined Closed-box Girder during Vortex-induced Vibration**

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**Abstract**

Mechanism of vortex-induced vibration (VIV) of bridges is an important prerequisite to evaluate and control that. The vortex-excited force (VEF) and its effects on structural behaviours are revealed in detail by synchronous analysis of multi-scale VEF, distributed aerodynamic force and structural responses during VIV. Aiming at a traditional streamlined closed-box girder of bridges, the time-frequency evolutionary characteristics during VIV are obtained via synchronous measurement of force and displacement responses of spring-suspended sectional model (SSSM). Results show that VEF of the model have obvious evolutionary characteristics in different periods, including pre-VIV period, ascent stage, amplitude extreme point, descent stage, and post-VIV period. The contribution of distributed aerodynamic forces to VEF and amplitudes of VEF are positively correlated with amplitudes of VIV responses, reaching the maximum at amplitude extreme point. Besides, the high-order harmonic components of VEF change significantly in lock-in region, and the ratio of the 2nd-order harmonic component to the fundamental component get the smallest value at the amplitude extreme point. In conclusion, the evolutionary characteristics of VEF and VIV responses are synergistic, especially nearby downstream region of upper surface and the corner region of lower surface and tail wind fairing, which is responsible for VIV.

**Introduction**

With increases in the spans of bridges, bridges become more flexible and small damping occurs. Therefore, the bridges more readily oscillate dramatically when subject to wind. The vortex- induced vibration (VIV) is just a typical phenomenon of wind-induced vibration, especially for the long-span bridges. Vertical VIV phenomenon have been found in the Trans-Tokyo Bay Bridge in Japan (Larsen et al., 2000), the Rio-Niteroi Bridge in Brazil (Fujino et al., 2002), the Great East Belt Bridge in Denmark (Ballista et al., 2000) , and the Xihoumen Bridge in China(Li et al., 2011). If the vortex shedding frequency is close to the natural frequency of the bridge, it can cause VIV. Although VIV is a kind of limited amplitude vibration and does not cause collapse, it can result in large displacements and discomfort to the drivers. The evolutionary characteristics of VEF on surface of the girder during VIV have been ignored to some extent in previous research, which is critical to understand the mechanism of VIV.

In this study, the evolutionary characteristics of VEF on surface of a streamlined closed-box girder during VIV, including pre-VIV period, ascent stage, amplitude extreme point, descent stage, and post-VIV period, are investigated, based on synchronous measurement of force and displacement responses of SSSM in wind tunnel. And then the mechanism of VIV are obtained.

The main research contents are as follows: Firstly, an linear empirical model of VEF, proposed by Scanlan (1986), is utilized to identify the aerodynamic parameters in lock-in region, and the evolutionary characteristics of VEF and corresponding components are obtained; Secondly, the contribution of the distributed aerodynamic forces to VEF, representing relationship between distributed aerodynamic forces and VEF, are analysed.

**Experimental Setups**



Fig.1 Geometrical sizes of a bridge sectional model (Unit :mm)

Fig.2 Layout and IDs of pressure taps



Fig.3 Schematic diagram of synchronous measurement system

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Fig.4 Schematic diagram of combination balances

A streamlined closed-box girder sectional model with an aspect ratio roughly 10:1 is used in this study to investigate evolutionary characteristics of aerodynamic forces. Considering that the VIV performance is always sensitive to the aerodynamic configuration

of bluff bodies, the deck exterior appearance, including the side fairings, hand rails, protection rails and maintenance traces, are modelled in the light of the principle of geometric similarity. The length of the sectional model is set to be 1.700m. The configuration of the cross section is illustrated in Fig. 1. A total of 81 pressure taps are arranged at the middle section of the model, as shown in Fig. 2. The approach of free vibration test of spring-suspended sectional model (SSSM) is used in this study to synchronously measure force and displacement responses. SSSM is installed on the self-developed adjustable system, with two Laser displacement sensors at each end, as shown in Fig.3. High-precision dynamic three-component balances are used at each end with double balance combination, as shown in Fig.4.

All experiments are conducted in TJ-3 boundary layer wind tunnel, which is a vertically arranged low-speed closed-circuit wind tunnel. The test section is 15.0 m wide and 2.0 m high. The wind velocity can be adjusted continuously from 1.0 m/s up to 17.6 m/s. The maximum blocking ratio, in consideration of sizes of model and system in tests, is less than 5%. The pressure measurement signals are corrected by the frequency response function of the tubes, avoid reducing or amplifying the pressure signals. Besides, considering pressure signals are corrected by the frequency response function, synchronous measurement of force, based on total forces as well as pressures, and displacement responses of SSSM are realized. The main parameters of SSSM are shown in Table 1.

|  |  |  |
| --- | --- | --- |
|  | 1st Vertical  | 1st Torsional |
| Frequency/Hz | 5.66 | 15.12 |
| Damp ratio/% | 0.35 | 0.35 |
| Total mass/kg | 13.09 |
| Total [mass moment of inertia](http://www.baidu.com/link?url=OFaLohtMOzmANfqvswjx1qJ2w6kpwZ5Zw4mxRNjxPrbRCLV5qTi52PShy3fP1b01txWkajf6BAbiD1EiYiwkGifNrbFirjoT1zFbM3Vj5D2-K2Ub3eKGYk7A6XGmDiAH&wd=&eqid=bd3919ce000d31890000000458e1a06c)/kg·m2 | 0.56 |

Tab.1 Main parameters of the SSSM

**VIV responses**

The tested wind velocities range from 2.0 to 7.0 m/s, with corresponding Reynolds number (Re) between 7.49×104 and 2.81×105. The experimental results show that there are no obvious VIV phenomenon at attack angle of -3 ° and 0°.The VIV responses at attack angle of + 3 ° are shown in Fig.5, where, denotes reduced velocity,is oncoming velocity,is the 1st vertical bending frequency,is normalized amplitude,is amplitude of vertical VIV. There are two vertical lock-in regions in the range of reduced velocity 0~26, and the 2nd lock-in region ranges from 16.3 to 22.5, with the maximum amplitude of 0.067 at the reduced velocity of 21.5. Due to limited space, only the 2nd lock-in region are analysed. In order to investigate the evolutionary characteristics of aerodynamic forces on surface of the model, reduced velocity of 15.6, 18.7, 21.5, 22.2 and 22.8 are taken as typical velocities during VIV, including pre-VIV period, ascent stage, amplitude extreme point, descent stage, and post-VIV period.



Fig.5 Vertical VIV responses

**Evolutionary characteristics of VEFs**

Based on the synchronous measurement technology, VEFs can be obtained by means of pressure-based method and force measurement method respectively. Then the evolutionary characteristics of VEFs and corresponding components are analysed, paving the way for relationships between VEFs and distributed aerodynamic forces.The lift is calculated by means of the 81 pressure taps. The measured dynamic pressures, which act normal to the surface, is weighted by the half distance to the neighbouring pressure taps and transformed in the coordinate system of the wind axis.



Fig.6 Time history of VEF



Fig.7 Amplitude spectrum of VEF

Fig. 6 and Fig. 7 show time history and amplitude spectrum of the VEF at reduced velocity of 21.5 respectively. It is obvious that it is not completely sinusoidal, due to the limitations of pressure-based method. Besides, there is a 2rd-order harmonic component (11.42 Hz) in addition to the predominant frequency of 5.71Hz, which reflects the non-linear characteristics of VEF.





Fig.8 Amplitude spectrum of VEF. (a) at reduced velocity of 18.7(ascent stage)；(b) at reduced velocity of 22.2(descent stage)

The time history and amplitude spectrum of VEF in different periods of lock-in region are obtained in order to reveal evolutionary characteristics of VEF in VIV process, as shown in Fig.8. There is no significant predominant frequency in non-VIV region. After entering the lock-in region, VEFs are controlled by the motion of the model. Thus, the predominant frequency of the VEFs are consistent with the predominant frequency of motion of the model, which is remarkably different from those in non-VIV region. The ratio of the 2nd-order harmonic and the 3rd-order harmonic to the fundamental one is 32.1% and 5.0% respectively at ascent stage. The amplitude of fundamental harmonic at amplitude extreme point is greater, compared with that at ascent stage. However，the second harmonic is obviously reduced，with the ratio to fundamental one 6.0%.Then the amplitude of VEF at the predominant frequency is greatly reduced, but the ratio of the second harmonic to the fundamental one rises to 19.7% at descent stage.



Fig.9 Comparison between amplitudes of VEF at predominant frequency and VIV responses during VIV

Fig. 9 shows the relationships between the amplitudes of VEF and the normalized amplitudes of VIV responses during VIV. It is obvious that the amplitudes of VIV are positively correlated with the amplitudes of VEF at the predominant frequency, reaching the maximum at amplitude extreme point.

In order to further reveal the evolutionary relationship between VEF and amplitude of VIV during VIV, the evolutionary characteristics of each component of VEF are analysed by linear empirical model of VEF based on the measured force signals. The mathematical model can be expressed as followed

  (1)

where, denotes the measured VEF; is the frequency of forced force, assumed to be the same as the VIV frequency; the polynomial item of ､andrepresent the aerodynamic damping term, the aerodynamic stiffness term and the aerodynamic forced term of VEF respectively, and the first and second term correspond to the self-excited component, while the third term represents the forced component. When the value ofis positive, the total damping ratio of the system decreases; is the phase lag between the forced item and the motion of the model.

Aerodynamic parameters can be identified by performing the least squares method during VIV. Fig.10(a) shows comparison between the measured time history of VEF and computed time history of VEF, resulted from aerodynamic parameters identified by least squares method. They fit well in both amplitude and phase, it is also obvious that VEF obtained by the force method is closer to the sinusoidal curve than pressure-based method，compared with Fig. 9. The VEF is further divided into three parts: aerodynamic damping item, aerodynamic stiffness item and forced force item. The time history of each component are shown in Fig.10 (b). The predominant frequency of the three component item are the same as the frequency of VIV. furthermore, the phase lag with the VEF is -35.04 °, 54.96 ° and 168.72 °respectively, while the ratio of component amplitude to VEF is 93%, 59% and 27%, respectively. Typical velocities are selected to identify the aerodynamic parameters in lock-in region, as shown in Table 2.



Fig.10 Time history of VIV forces. (a) comparison between measured VEF and computed VEF；(b) aerodynamic damping item, aerodynamic stiffness item and forced force item and measured VEF

The VEFs tend to have a much higher proportion of self-excited components than forced component. Entering lock-in region, the total damping ratio decreases and the amplitude of VIV increases gradually till the amplitude extreme point, then the total damping ratio increases rapidly and the amplitude decreases rapidly till entering non-VIV region. The aerodynamic negative damping effects on the model are the most important factor to stimulate VIV and maintain the high amplitude of VIV responses，which is also responsible for VIV responses and VEF evolutionary characteristics during VIV.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Reduced velocity |  |  |  |  |
| 19.0 | 2.0823 | -2.0168 | 0.0175 | 3.4197 |
| 20.1 | 2.1200 | -1.4620 | 0.0175 | 2.5685 |
| 20.8 | 2.1560 | -3.4599 | 0.0178 | 3.2385 |
| 21.5 | 2.2040 | -4.4506 | 0.0180 | 2.1360 |
| 22.5 | 1.5866 | -0.9646 | 0.0190 | 1.4644 |

Tab.2 Aerodynamic parameters of linear empirical model during VIV

**Correlation between aerodynamic force and VEFs**

The contribution of distributed aerodynamic forces to VIV on surface of the model depend on both amplitudes of the aerodynamic forces at the measuring tap and its correlation with VEF. So the contribution value at each measuring tap can be expressed as followed

 (2)

where, denotes RMS of pressure coefficient at measured tap ;is the correlation between distributed aerodynamic forcesand VEF, denotes length nearby measured tap.

Fig. 11 shows the spatial distribution characteristics of contribution values during VIV. The contribution values vary remarkably in the downstream region of the upper surface, the lower region of the windward side, the upper region of the leeward side and the downstream part of the lower surface,especially nearby downstream region of upper surface (defined as region A) and the corner region of lower surface and tail wind fairing(defined as region B).The contribution values at different periods is significant, and positively correlated with the amplitude in lock-in region.

In order to further reveal the synchronous evolutionary relationships between amplitudes of VIV responses and the contribution values, the measurement tap of No.18 on upper surface and No.33 on lower surface are selected as [representative](http://www.so.com/link?url=http%3A%2F%2Fdict.youdao.com%2Fsearch%3Fq%3Drepresentative%26keyfrom%3Dhao360&q=representative&ts=1493251368&t=38350e49b80a90579709101a1544a46)s of region A and region B respectively. Fig.12 shows the relationships between the normalized amplitude of VIV and contribution value of A as well as B. The amplitude of VIV varies with that of A and B in the same trend, and reach maximum value at amplitude extreme point during VIV .

The contribution of aerodynamic forces to VIV are obviously different between lock-in region and non-VIV region. The contribution values are limited in non-VIV region, while aerodynamic forces nearby downstream region of upper surface and the corner region of lower surface and tail wind fairing contribute mostly to VEF, and are positively correlated with amplitude of VEF, reaching the maximum value at amplitude extreme point. Thus, aerodynamic forces in these regions contribute mostly to VIV.



Fig.11 Spatial distribution characteristics of contribution values during VIV



Fig.12 Comparison of contribution values of typical pressure taps during VIV

**Conclusions**

Aiming at the typical girder, which is often used in large-span bridges, evolution characteristics of VEF on surface of model in different periods, including pre-VIV period, ascent stage, amplitude extreme point, descent stage, and post-VIV period are studied. Then mechanism of VIV of the typical streamlined box girder were revealed. The main conclusions are as follows:

1. Aerodynamic characteristics on surface of model obviously change during VIV, and aerodynamic characteristics in lock-in and non-VIV region are remarkably different. Contribution of distributed aerodynamic forces to VEF are limited in non-VIV period, while aerodynamic forces nearby downstream region of upper surface and the corner region of lower surface and tail wind fairing contribute mostly to VEF. The aerodynamic negative damping effects on the model are the most important factor to stimulate VIV and maintain the high amplitude of VIV responses，which is responsible for VIV responses and VEF evolutionary characteristics during VIV.
2. Aerodynamic forces and amplitudes of VIV responses are evolved synchronously, both the contribution of distributed aerodynamic forces to VEF and amplitudes of VEF are positively correlated with amplitudes of VIV responses during VIV.
3. High-order harmonic components of VEF change significantly in lock-in region. The 2nd-order harmonic component to the fundamental one is as high as 32.1% at ascent stage, and then reduced to 6.0% at amplitude extreme point, rebound to 19.7% at descent stage at last.

In conclusion, the evolutionary characteristics of VEF and VIV responses are synchronous, especially nearby downstream region of upper surface and the corner region of lower surface and tail wind fairing, which is responsible for VIV.

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