Experimental Investigation Concerning Aerodynamic Stability of a Stay Cable Incorporated with Lamps

Shou-Ying Li and Zheng-Qing Chen

1 Associated Professor, Wind Engineering Research Center, Hunan University, Changsha 410082, China, shyli@hnu.cn

2 Professor, Wind Engineering Research Center, Hunan University, Changsha 410082, China, zqchen@hnu.cn

Abstract

Lamps installed on cables of cable-stayed bridge may alter the geometry of cable cross section and therefore render the stay cables aerodynamically unstable under the action of the wind. By taking a preliminary design of lamp installation scheme on cable-stayed He-dong Bridge, China, as an example, sectional models of stay cable and lamp is made with the geometrical scale of 1:1. Wind tunnel tests were then both carried out to obtain aerodynamic forces and check the occurrence of galloping. Results show that galloping will take place in the preliminary design due to the presence of two parallel steel wires. A modification that cancels the two parallel steel wires is thus put forward. Detailed wind tunnel tests were finally carried out to check the galloping instability of the cable with proposed modification, and small vibration amplitudes are found.

KEY WORDS: STAY CABLE, GALLOPING, WIND TUNNEL TEST, LAMP INSTALLATION, AERODYNAMIC FORCE COEFFICIENTS

1 Introduction

Due to low frequencies and low damping ratios, cables on cable-stayed bridge experience several types of wind induced vibration, such as rain-wind induced vibration [Hikami et al. (1988)], buffeting [Lu et al. (2001)], vortex induced vibration [Matsumoto et al. (2001)], parameter vibration [Tagata et al. (2001)], and so on. Rain-wind induced vibration was firstly observed on MekoNishi Bridge in Japan, and it happens under the combined action of wind and rain. The mechanism of rain-wind induced vibration is currently not clearly clarified, though the upper rivulet on cable surface is believed to a key factor. Buffeting of stay cable is induced by the fluctuating velocity in the approaching flow. When wind flow passes through a stay cable, a vortex will be produced. If the frequency of the vortex is equal (or close) to one of the natural frequencies of stay cable, vortex induced vibration of stay cable will happen. Parameter vibration happens when the frequency of main beam oscillation is two times of one of the natural frequencies of stay cable. These kinds of cable vibrations mentioned above severely affect the safety of cable-stayed bridges, especially rain-wind induced vibration. Some measures have been put forward to mitigate these kinds of cable vibrations, such as changing the surface configuration of the cable [Flamand et al. (1995)], installing damper near the beam end [Chen et al. (2004)], or connecting several cables by cross tie [Yamaguchi et al. (1995)]. The stay cable with circular cross section generally is aerodynamically stable in terms of galloping [Simiu et al. (1996)]. But for some purposes, such as esthetics or illumination, some additional equipment may be installed on stay cables.
of cable-stayed bridges. Such equipments alter the circular cross section of stay cable to non-circular, and may result in galloping vibration.

He-dong Bridge is a cable-stayed bridge located at Guangzhou City, Guangdong Province, People’s Republic of China. Its main span is 360 m long, its side span is 144 m long, the height of its pylon towers is 128.4 m, and the longest cable is 191.7 m. For illumination, lamps were planned to install on the cables of He-dong Bridge with an interval of 1.2 m. The lamp cross section was circular with a diameter of 0.262 m and a height of 0.17 m, as shown in Fig.1. In order to decrease the additional force on the cable as well as for the convenience of lamps installation, two parallel steel wires were designed along both sides of the cables. The diameter of the parallel steel wires was 12 mm, and the distance of the two parallel steel wires was 0.215 m, as illustrated in see Fig.2. One end of steel wires was fixed on the pylon tower, and the other end was fixed on the main beam. These two parallel steel wires changed the symmetric cross section of the cable into an asymmetrical one, and it may result in a violent cable oscillation of galloping. In this paper, the aerodynamic stability of the cable and lamp system in the preliminary design of He-dong Bridge is investigated in wind tunnel, including wind forces measurement by force balance technique and vibration response measurement by a one-degree-of-freedom model system. Results show that this preliminary design would result in violent cable oscillation of galloping. Then, some proposed modification, which is aerodynamically stable, is suggested and validated through wind tunnel testing.

Fig.1: Photo of Lighting Lamp  
Fig.2: Preliminary Design of Lamp Installation on He-dong Bridge

2 Experimental Setup and Test Model

Wind tunnel tests were carried out in the 3 m wide by 2.5 m high by 17 m long test section of the HD-2 Boundary Layer Wind Tunnel (HD-2BLWT) in Wind Engineering Research Center, College of Civil Engineering, Hunan University, China. Maximum wind velocity of the HD-2BLWT in this test section is 60 m/s provided by its 617 KW propeller. HD-2BLWT is a horizontal closed-circuit type wind tunnel which possesses two test sections. Another test section is 5.5 m wide by 4.4 m high by 15 m long with a maximum wind velocity of 18 m/s. Test model was made the same size of proto-type cable and lamp, that is 1/1 scale, so Reynolds number was completely simulated. The length of the cable and wire was 1.2 m with the lamp at their center. The cable diameter was selected as 0.1 m (the diameters of He-dong Bridge are from 0.085 m to 0.145 m), the wires’ diameter was 0.012 m. Three net distances of the two parallel wires, d=0.215 m, 0.158 m and 0.1 m, were selected in this test. The material of these models was organic glass.

Two types of wind tunnel tests were carried out. The first was the measurements of drag and lift of the cable-lamp model by force balance method, as shown in Fig.3 (a)), the second test was vibration measurements of a one-degree-of-freedom suspension system. For
convenience of model visibility, cable, lamp and steel wires were respectively painted with blue, yellow and red paints, respectively in vibration measurement test, see Fig.3 (b). Force measurement tests were carried out in uniform wind with a velocity of 10 m/s. Vibration measurement tests were also carried out in uniform wind with velocities ranging from 3 m/s to 30 m/s and a velocity interval of 0.5 m/s. The highest wind velocity tested was set to 30 m/s to ensure safety of the model and facilities in closed-circular wind tunnel, and it was enough in this wind tunnel test as will be shown later.

Wind attack angle was defined following Fig.4, and the positive directions of mean lift and mean drag, FL and FD, were also showed in Fig.4. The model’s cross section is symmetrical about two axes, so force measurement tests were only carried out in wind attack angle \( \alpha \) of \( 0^\circ - 90^\circ \) with an interval of \( 2^\circ \). On the other hand, vibration measurement tests were carried out only at some particular wind attack angles, which determined by the mean lift and drag from force measurement tests.

A six-component static force balance, HD100, was adopted to measure the mean lift and drag forces of the model. The measuring range of HD100 is 1200 N for concentrated forces and 200 N\( \cdot \)m for moments. In vibration measurement tests, four springs (two for each end) were adopted to suspend the segmental model. Each spring is connected to a load sensor, by which the tensile forces of the spring can be collected. Then the displacement time history of the cable and lamp model can be derived from the four-spring tensile forces.

(a) Test Model of Lift and Drag Measurements  (b) Test Model of Vibration Measurement

Fig.3: Photos of Test Model in Wind Tunnel

![Fig.3: Photos of Test Model in Wind Tunnel](image)

Fig.4: Definition of Wind Attack Angle

![Fig.4: Definition of Wind Attack Angle](image)
3 Test Results and Discussions

The mean lift and drag coefficients of the cable and lamp model, $C_L$ and $C_D$, can be respectively defined as follows [Holmes et al. (2001)],

$$C_L = \frac{2F_L}{\rho U^2 DL}$$

$$C_D = \frac{2F_D}{\rho U^2 DL}$$

in which, $F_L$ is the mean lift force of the cable and lamp model; $F_D$ is the mean drag force of the cable and lamp model; $\rho$ is the air density, $\rho=1.225$ kg/m$^3$; $U$ is the approaching wind velocity; $D$ is the cable diameter; $L$ is the length of the cable and lamp model.

2.1 Mean Lift and Drag Coefficients

Fig.5 (a), (b) and (c) give the mean lift and drag coefficients ($C_L$ and $C_D$) of the cable and lamp model when the distance of two parallel steel wires, $d$, is equal to 0.215, 0.158 and 0.1 m, respectively. In general, because of the circular cross section of stay cable, the mean lift and drag coefficients of the cable are both equal to constants under every wind attack angle $\alpha$, in which, $C_L=0$, $C_D$ is related to Reynolds number ($Re=\rho UD/\mu$) [Simiu et al. (1996)]. So galloping will not take place as a result of Den Hartog Theory [Chen et al. (2005)]. But owing to the two parallel steel wires in the preliminary design of lamp installation of He-dong Bridge, the circular cross section of the cable is changed, and the mean lift and drag coefficients vary with wind attack angle $\alpha$, see Fig.5. The mean lift coefficients when $d=0.215$, 0.158 and 0.1 m all have an obvious abrupt decrease at proper range of wind attack angle. The largest decreases of the mean lift coefficients happens in the wind attack angle ranges of $\alpha=12^\circ$–$22^\circ$ ($d=0.215$ m), $\alpha=24^\circ$–$28^\circ$ ($d=0.158$ m) and $\alpha=28^\circ$–$34^\circ$ ($d=0.1$ m). According to well-known Den Hartog Theory, necessary condition of galloping is [Chen et al. (2005)],

$$dC_L/d\alpha + C_D < 0$$

That is, the galloping can take place only when galloping force coefficient is negative. On the basis of Fig.5, the galloping force coefficients when $d=0.215$m, 0.158m and 0.1 m can be obtained, and is shown in Fig.6. For the convenience of analyzing, the smallest galloping force coefficients and its corresponding wind attack angle are listed in Tab.1. From Fig.5 and Fig.6, it can be found that cable galloping might take place if the lamp is installed according to the preliminary design. It should be noted that the smallest galloping force coefficient of $d=0.1$ m (two parallel steel wires are just on the cable) is greater than those of $d=0.215$ m and 0.158 m.

Besides the wind attack angle ranges mentioned in Tab.1, there are other wind attack angle ranges in which the galloping force coefficient is negative, such as $\alpha=45^\circ$ when $d=0.158$ m and $\alpha=40^\circ$–$55^\circ$ when $d=0.1$ m. In these wind attack angle ranges, galloping might take place too.

![Fig.5: The Mean Lift and Drag Coefficients of The Cable and Lamp Model](image-url)
From the results of the mean lift and drag coefficients, it is concluded that galloping will take place on the cable with this kind of lamp installation. Now, vibration measurement test by using a one-degree-of-freedom suspension system was carried out for further validation. Because galloping is a type of cross-wind vibration, only a vertical degree-of-freedom is considered in the suspension system of vibration measurement test. The motion equation of the cable and lamp model is written as,

\[ m_y (\ddot{y} + 2\zeta_m \omega_m \dot{y} + \omega_m^2 y) = \frac{1}{2} \rho U^2 D (\frac{dC_L}{d\alpha} + C_D) \frac{\dot{y}}{U} \]  

in which, \( m_m \) is the model mass per unit length; \( \zeta_m \) is the damping ratio of the model; \( \omega_m \) is the circular frequency of the model. By letting the sum of structural damping and aerodynamic damping to zero, the galloping critical wind velocity of this cable and lamp model can be written as [Chen et al. (2005)],

\[ U_{gm} = \frac{-4m_m \zeta_m \omega_m}{\rho D (dC_L/d\alpha + C_D)} \]  

The mass per unit length of the vibration model (including additional weight) \( m_m \) is 6.28 kg; the damping ratio of the suspension system \( \zeta_m \) is 1.0%; the natural circular frequency of the suspension system \( \omega_m \) is 6.28 rad/s.

According to modal superposition method, the motion equation of the \( i^{th} \) mode of a proto-type continuous stay cable can be written as [Clough et al. (2003)],

\[ m_i (\ddot{y}^i + 2\zeta_i \omega_i \dot{y}^i + \omega_i^2 y^i) = F_i(x, t) \]  

in which,
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\[ m^*_i = \int_0^l m \phi^2(x) dx \quad F^*_i(x,t) = \int_0^l \left[ \frac{1}{2} \rho U^2 D \frac{dC_e}{d\alpha} + C_D \right] \frac{\dot{y}}{U} \phi_i(x) dx \]  

(7)

Only the first mode of the longest cable of He-dong Bridge is considered in this paper because the galloping critical wind velocity corresponding to this mode is the smallest one. The first natural circular frequency of the longest cable of He-dong Bridge is 4.913 rad/s; the mass per unit length is 68.4 kg/m; the damping ratio is approximately 0.1%; the first mode function can be approximately obtained as,

\[ \phi_i(x) = \sin \frac{\pi x}{l} \]  

(8)

where, \( l \) is the cable length. Then the generalized mass \( m^*_i \) and the generalized force \( F^*_i(x,t) \) can be written as,

\[ m^*_i = \frac{l}{2} m \quad F^*_i(x,t) = \frac{1}{\pi} \rho U^2 D \left( \frac{dC_e}{d\alpha} + C_D \right) \frac{\dot{y}}{U} \]  

(9)

From equations (6) and (9), the galloping critical wind velocity for the first mode of the longest cable of He-dong Bridge is,

\[ U_{gp} = \frac{\pi}{4} \frac{-4m\zeta\omega}{\rho D (dC_e/d\alpha + C_D)} \]  

(10)

Comparing equations (5) and (10), the ratio of galloping critical wind velocity of the first mode of the longest cable of He-dong Bridge to the test model, \( U_{gp}/U_{gm} \), is 0.614.

The distance of 0.215 m between the two parallel steel wires, which is with the same as the preliminary design, was selected in the vibration measurement test. The setup is shown in Fig.3 (b). It can be found from the results of section 2.1 (Tab.1) that galloping force coefficient is the smallest one when \( \alpha=19^\circ \) if \( d=0.215 \) m. In the vibration measurement test, wind attack angle \( \alpha \) was fixed to 19\(^\circ\), and wind velocity started from 3 m/s with an interval of 0.5 m/s. When wind velocity arrived at 18 m/s, which corresponds to 11.1 m/s of the first mode of the longest cable of He-dong Bridge, large amplitude of galloping vibration happens. It is dangerous to test model to further increase wind velocity for the safety consideration of wind tunnel, so wind velocity stopped at 18 m/s. In order to protect the test model, the largest peak-to-peak amplitude was restricted to 0.08 m. Fig.7 gives the displacement time history of the test model when wind velocity is 18 m/s.

From Fig.7, one can find that galloping would take place if the preliminary design is put into practice. Therefore, a modification to this preliminary design or a new design should be put forward to avoid the dangerous galloping vibration.

4 Proposed Modification and its validation

From the both results of the above force and vibration measurement tests, it can be found that large amplitude of galloping vibration will take place when wind attack angle \( \alpha=19^\circ \) under the condition of the preliminary design with two parallel steel wires. The two parallel steel wires, which change the aerodynamic forces of the cable and lamp model, are the key factor for galloping. Even if the distance of the two wires becomes smaller, for example, \( d=0.158 \) m and 0.1 m, the possibility of galloping vibration also exists, as shown in Tab.1.

In this paper, the two parallel steel wires are proposed to be cancelled, and the electric wires of the lamps twist the cable helically. Helical line is an effective measure to mitigate the rain-wind induced vibration of stay cables, and its effectiveness has been validated by some
wind tunnel tests [Gu et al. (2005)] and some applications on proto-type bridges, such as Normandy Bridge in France [Virlogeux et al. (1998)], Nanjing Second Yangtze River Bridge in China.

The effectiveness of the proposed modification was validated by vibration measurement test in wind tunnel. The photo of test model suspended in wind tunnel is shown in Fig.8. The parameters of the cable and the lamp are same to those introduced in section 1. The electric wires of the lamps (on both side of the cable) are simulated by soft white ropes with a diameter of 8 mm. Between adjacent lamps, the electric wires twist in an angle of 20º, see Fig.9. Fig.9 also gives the definition of wind attack angle $\alpha$. The mass per unit length of the test model is 6.28 kg/m; the damping ratio is 0.5%; the circle frequency is 6.28 rad/s.

According to equations (5) and (10), the ratio between the galloping critical wind velocity of the first mode of the longest cable of He-dong Bridge to the test model, $U_{gp}/U_{gm}$, is now 1.228.

In the vibration measurement test of the proposed modifications, a wind attack angle range of $\alpha = 0^\circ - 90^\circ$ with an interval of 5º was adopted. For each wind attack angle, wind velocities changed from 4 m/s to 30 m/s with a velocity interval of 0.5 m/s. The results show that the cable and lamp model has small amplitude of vibration under any wind velocity at any wind attack angle, so galloping does not take place. The displacement time histories of the test model under wind velocity of 30 m/s at any wind attack angle were recorded by the two load sensors connected to springs.

Fig.10 gives the vertical displacement time history of the test model when $\alpha = 0^\circ$ and $60^\circ$, wind velocities are 30 m/s, which is corresponding to 36.8 m/s of the first mode of the longest cable of He-dong Bridge. From Fig.10, one can find that the largest amplitude of the test cable is less than 10 mm. The wind velocity for a return period of 100 years in Guangzhou is 31 m/s, which is less than 36.8 m/s. So, this type of lamp installation will not result in the dangerous vibration of galloping.
5 Conclusions

By taking a preliminary design of lamp installation on cables of He-dong Bridge as an example, both force measurement and vibration measurement wind tunnel tests were carried out. The results show that galloping will take place if the lamps are installed on the cables according to the preliminary design. For a proposed modification, the two parallel steel wires in preliminary design are cancelled, and the electric wires of the lamps are proposed to twist the cables helically. Vibration measurement test was carried out to validate the effectiveness of the proposed modification. The results show that galloping is well mitigated.

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References

M. Virlogeux. Cable vibrations in cable-stayed bridges. In Bridge Aerodynamics, Balkema, Rotterdam: 1998,