*Wind and Structures, Vol. 16, No. 3 (2013) 249-261*
DOI: http://dx.doi.org/10.12989/was.2013.16.3.249


# Wind-tunnel study of wake galloping of parallel cables on cable-stayed bridges and its suppression

Yongle Li[*1], Mengxue Wu[1], Xinzhong Chen[2], Tao Wang[1] and Haili Liao[1]

*[1]Department of Bridge Engineering, Southwest Jiaotong University, Chengdu, Sichuan 610031, P. R. China*
*[2]Wind Science and Engineering Research Center , Department of Civil and Environmental Engineering, Texas Tech University, Lubbock, Texas 79409-1023, USA*

*(Received July 27, 2011, Revised March 22, 2012, Accepted March 22, 2012)*

**Abstract.** Flexible stay cables on cable-stayed bridges are three-dimensional. They sag and flex in the complex wind environment, which is a different situation to ideal rigid cylinders in two-dimensional wind flow. Aerodynamic interference and the response characteristics of wake galloping of full-scale parallel cables are potentially different due to three-dimensional flows around cables. This study presents a comprehensive wind tunnel investigation of wake galloping of parallel stay cables using three-dimensional aeroelastic cable models. The wind tunnel study focuses on the large spacing instability range, addressing the effects of cable separation, wind yaw angle, and wind angle of attack on wake galloping response. To investigate the effectiveness of vibration suppression measures, wind tunnel studies on the transversely connected cable systems for two types of connections (flexibility and rigidity) at two positions (mid-span and quarter-span) were also conducted. This experimental study provides useful insights for better understanding the characteristics of wake galloping that will help in establishing a guideline for the wind-resistant design of the cable system on cable-stayed bridges.

**Keywords:** cable-stayed bridge; parallel cables; wake galloping; wind tunnel test; cable dynamics; vibration suppressing measures

## 1. Introduction

With extension of the span length of cable-stayed bridges, wind loads have become one of the predominant loads in the design of cable-stayed bridges. Stay cables are extremely vulnerable to various different kinds of vibrations under wind excitation, largely due to their low mass and mechanical damping. According to extensive wind tunnel studies and field observations, wind-induced cable vibration includes: (a) vortex-induced vibration; (b) buffeting; (c) rain-wind-induced vibration; (d) parametric vibration; (e) drag instability; (f) classical galloping; (g) dry inclined cable vibration; (h) wake-induced galloping or flutter and resonant buffeting (e.g., Tanaka 2003, Xu *et al.* 2005, Kumarasena *et al.* 2005). Wake galloping or flutter occurs in the downstream cable when it is submersed in the wake of the upstream cable due to aerodynamic interference. Extensive investigations have been performed concerning the flows around two

[*]Corresponding author, Professor, E-mail: lele@swjtu.edu.cn

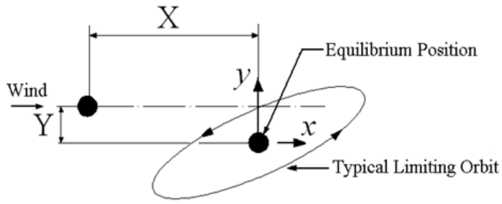



Fig. 1 Wake galloping phenomenon

circular cylinders, their aerodynamic forces and the vibration characteristics using two-dimensional section models of parallel cylinders in wind tunnels to clarify the generation mechanism and characteristics of wake galloping (Cooper and Wardlaw 1971, Zdravkovich and Pridden 1977, Zdravkovich 1977, 1987, 1988, Cooper 1985, Maeda and Kubo 1997, Irwin 1997, Gu and Sun 1999, Brika and Laneville 1997, PTI 2001, Tokoro and Komatsu 2000, Tanaka 2003, Hata *et al.* 2004, Miyata *et al.* 2004, Williams and Suaris 2006). Parameters influencing wake galloping include the separation between twin cables, wind direction, and Scruton number. Three primary interference regions, measured by the distance of twin cylinders, can be classified as "close spacing" unstable range, stable range, and "large spacing" unstable range (e.g., Tanaka 2003).

(1) "Close spacing" unstable range: Aerodynamic flow around two cylinders is significantly altered by aerodynamic interference. Instability is often observed in the range of $-2 \le Y/D \le 2$ and $1 < X/D < 4$, where *Y* is the distance in the cross-flow direction; *X* is the distance in the flow direction; and *D* is the diameter of the cylinder (Fig. 1). Vibration generally starts at the critical reduced flow speed of $U_{cr}/fD \approx 40$, where *f* is natural frequency of the cylinder, and follows an elliptical trajectory with the maximum amplitude of less than 3D. The vibration is sensitive to the Scruton number *Sc* ($S_c = m\zeta / \rho D^2$, where *m* is cable mass per unit length; $\zeta$ is the damping ratio; $\rho$ is the air density.) and becomes hardly recognizable when *Sc*>50.

(2) Stable range: As the spacing of two cylinders increases, there is a stable range before the next "large spacing" unstable range is reached.

(3) "Large spacing" unstable range: When the spacing is about $8 < X/D < 20$, the interference effects are only on the flow around downstream cylinder. The vibration of the downstream shows an elliptical path with its major axis roughly aligned with the wind direction.

Previous wind tunnel studies of wake galloping of twin circular cylinders and stay cables have been based on spring-supported rigid sectional models in two-dimensional wind flow, while a limited number of investigations have been performed using aeroelastic models (Cooper and Wardlaw 1971, Tokoro *et al.* 2000, Hu and Zhao 2006). An approximate equation for the critical wind speed $U_{cr}/fD$ of wake galloping of parallel cables has been proposed (Cooper 1985, Irwin 1997, PTI 2001), which is a function of Scruton number as $U_{cr}/fD = c\sqrt{S_c}$, where *c* = 25 for closely spaced cables (2D-6D spacing), and *c* = 80 for normally spaced cables (generally 10D and higher). It is emphasized that flexible stay cables in cable-stayed bridges are three-dimensional. They sag and flex in the complex wind environment, and are different from ideal rigid cylinders in two-dimensional wind flow. Aerodynamic interference and the response characteristics of wake galloping of full-scale parallel cables are potentially different due to three-dimensional flows around cables.

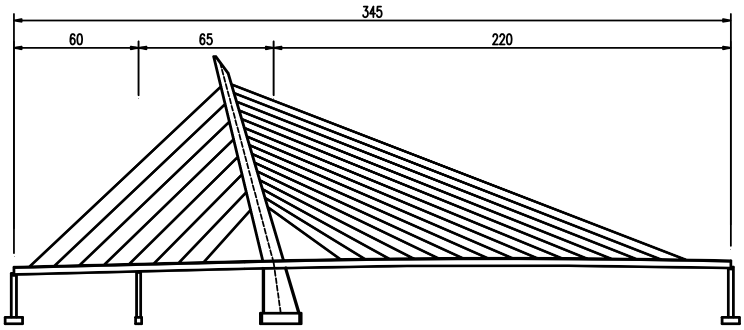



Fig. 2 General outline of the bridge (Unit : m)

In the present study, a wind tunnel study of wake galloping of parallel stay cables is performed using three-dimensional aeroelastic cable models. The wind tunnel test focuses on the large spacing unstable range, addressing the effects of cable separation, wind yaw angle, and wind angle of attack on wake-galloping response. To investigate the effectiveness of the measures for suppressing the vibration, the transversely connected cable systems with two types of connections (flexibility and rigidity) at two positions (mid-span and quarter-span), were also investigated in the wind tunnel. The experimental data and conclusions drawn from this study help in better understanding the characteristics of wake galloping, and provide useful information for establishing a wind-resistant design guideline of the cable system in cable-stayed bridges.

## 2. Wind tunnel testing

### 2.1 Description of the cable-stayed bridge

This cable-stayed bridge had a single inclined tower and single cable plane with the spans of 60 m+65 m+220 m as shown in Fig. 2. A steel box girder was used in the main span, while prestressed concrete box girder was used in the side spans. These two types of girders have the same profile with a depth of 3.3 m and upper width of 34 m. The tower was situated at the medial divider, in height of 98 m (above the deck), and inclined at 15° off the vertical. The stay cables were in a parallel arrangement, and the spacing of the twin cables gradually varied from 3.8 m (at the deck) to 1.0 m (at the tower), just in the range of 10D ~ 20D (D is the diameter of the full-scale cable, D = 133 mm). There was a possibility that the stay cables of this bridge could be excited by wake galloping. There was a need to investigate the characteristics of wake galloping for stay cables in this bridge through wind tunnel testing.

### 2.2 Cable model and test conditions

A stay cable model with a diameter of $D_m$ = 32 mm and a length of 2.85 m was employed in the test. The geometrical ratio of the model was $D_m/D_p$ = 1/ 4.156 (Diameter of the full-scale cable is $D_p$ = 133 mm). The cable model consisted of three components: polyethylene tube as the cover, steel cylinder as additional mass, and steel wire rope. The steel wire rope passes across holes coaxial to the axis of each cylinder that is fixed on the rope by lateral screws. These cylinders are adequately distributed to satisfy the requirement of mass similarity for the whole cable. The

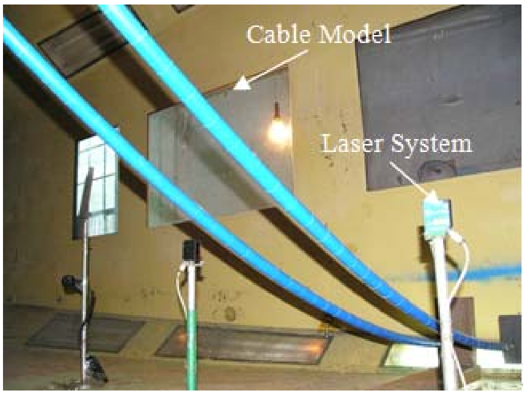



Fig. 3 Cable models in the wind tunnel

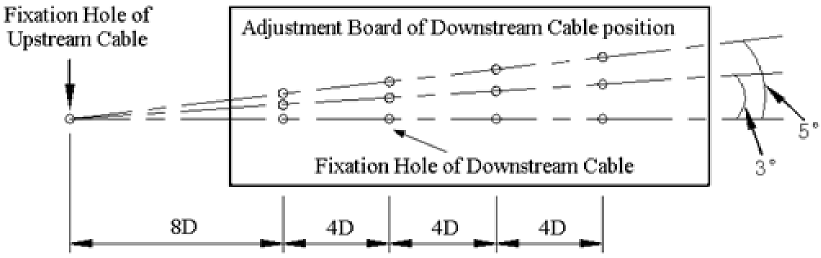



Fig. 4 Adjustment board of cable position

cylinder surface is covered with polyethylene tube as the “coat” of the cable, ensuring the geometrical similarity of the cable. Moreover, polyethylene tube is in a segmental arrangement to avoid additional stiffness. The whole stay cable was fixed at each end of the steel wire rope, and oscillation frequency of the cable was adjusted by changing tensile force of the rope. The model employed in the test was designed to have a relatively low structural damping. To obtain the more obvious vibration phenomena, no additional damping device was needed. In this test, the damping ratio of full-scale stay cable is approximately simulated. The damping ratios of the upstream and downstream cable are 0.212% and 0.197%, respectively, which are close to the typical value of damping ratio of stay cables in the range of 0.1~0.3%. We chose 0.200% as the damping ratio of the cable model. The mass per unit length of the full-scale cable was $m_p$ = 78.5 kg/m. The cable model should satisfy the requirement of mass similarity, so the mass per unit length of the cable model was $m_m = (D_m/ D_p)^2 \times m_p$ = 4.54 kg/m. Accordingly the Scruton number was $Sc = m\zeta / (\rho D^2)$ = 7.1.

The supporting system employed in the test consisted of two steel frameworks in the shape of a “U”. One side of the framework was high, and the other side was low. Hence different angles between the cable axis and the horizontal direction could be obtained. The bottom of the whole framework was connected with the turntable, and the wind yaw angle could be adjusted continuously through the turntable as shown in Fig. 3. The position of the upstream cable was kept fixed in the overall test process, while the horizontal and vertical positions of the downstream cable were changed through an adjustment board for cable position as shown in Fig. 4. In this way the variations of different spacing and angle of wind attack were achieved. Due to the same vibration frequency of two cables, the resonant oscillation easily takes place through the

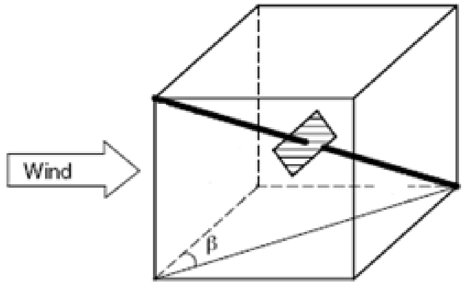



Fig. 5 Definition of wind yaw angle $\beta$

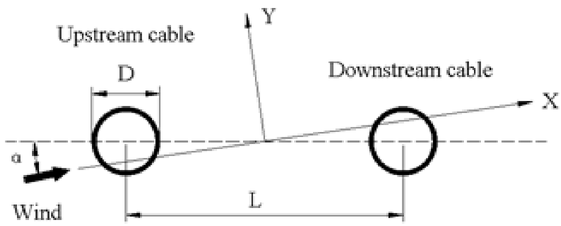



Fig. 6 Definition of wind attack angle $\alpha$

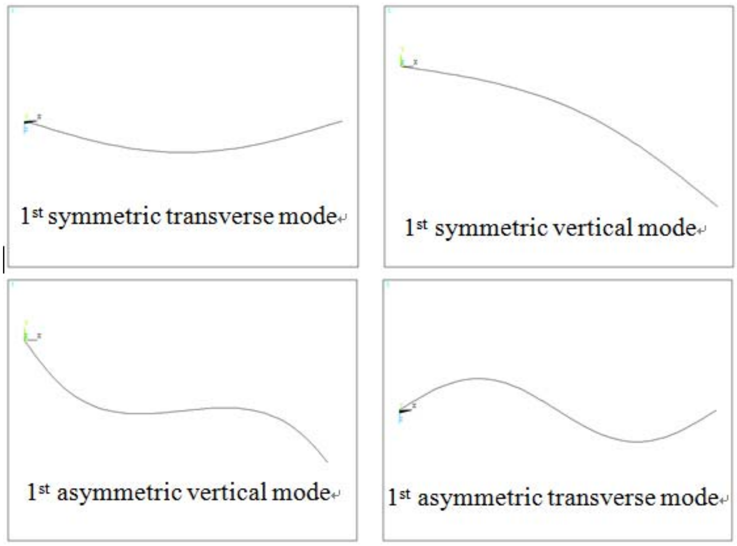



Fig. 7 First four mode shapes of the full-scale cable

supporting system. To avoid this vibration coupling, two cables were supported by two independent steel frameworks. In addition, the supporting frameworks were strengthened by steel wire ropes to increase their outside-plane stiffness.

The wind tunnel test was conducted in the first experimental segment in the Southwest Jiaotong University XNJD-1 wind tunnel with uniform flow, without consideration of the change in wind speed with height. In order to investigate the influences of cable separation, wind yaw angle (Fig. 5), and angle of wind attack (Fig. 6) on the cable vibration, the wind tunnel test involved a total of

Table 1 Modal properties of full-scale and model cables

| | Mode No. | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Full-scale cable | Frequency(Hz) | 1.099 | 1.104 | 2.199 | 2.199 |
| | Mode shape | Symmetrical transverse | Symmetrical vertical | Asymmetric vertical | Asymmetric transverse |
| Model cable | Frequency(Hz) | 1.274 | 2.497 | 2.544 | 3.607 |
| | Frequency (Hz) (Measured) | 1.270 | 2.539 | 2.637 | 3.516 |
| | Mode shape | Symmetrical transverse | Asymmetric vertical | Asymmetric transverse | Symmetrical vertical |

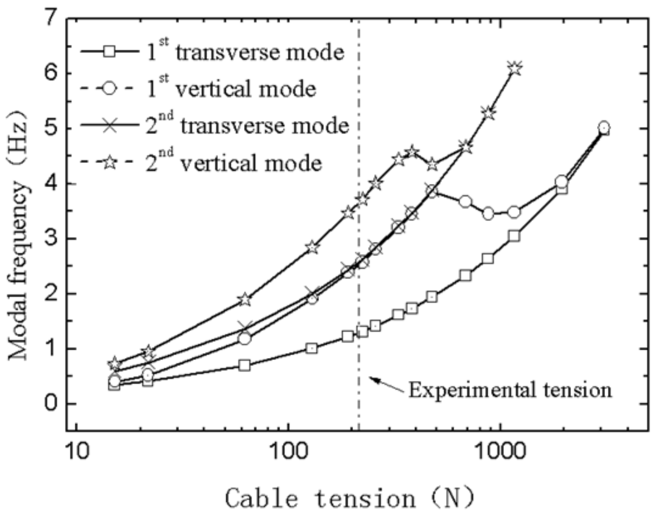



Fig. 8 Variations of frequencies of model cable with changing cable tension

48 testing cases, which includes four different cable spacing (8D, 12D, 16D, 20D), four different yaw angles (0°, 10°, 20°, 30°), and three different angles of attack (0°, 3°, 5°). The maximum wind speed was 23 m/s, corresponding to the wind speed of 81 m/s in the full-scale bridge, higher than the verification wind speed of wake galloping of 71.4 m/s required by this bridge. Laser displacement instruments (Fig. 3) were employed to measure the displacements of the cables in both transverse and vertical directions at mid-span and quarter-span, respectively.

### *2.3 Dynamic characteristics of the model cable*

Table 1 and Fig. 7 show the first two modal frequencies and shapes of the full-scale stay cable in both transverse and vertical directions, which were calculated from a three-dimensional finite element model with consideration of sag. As expected, due to higher tensile force and small sag in full-scale stay cables, the frequencies of transverse and vertical oscillation modes are approximately the same, and the corresponding mode shapes are very similar. The first modes feature symmetric mode shapes while the second modes are asymmetric. The ratio of second to first mode frequencies is 2.

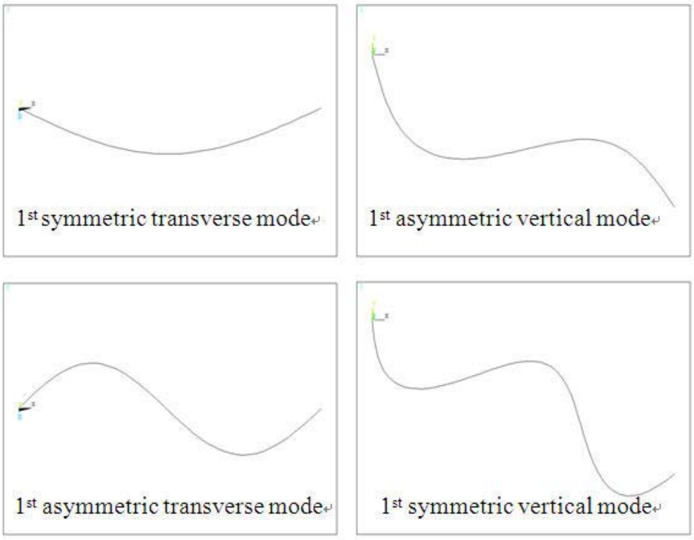
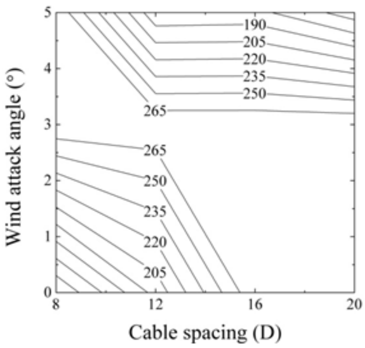


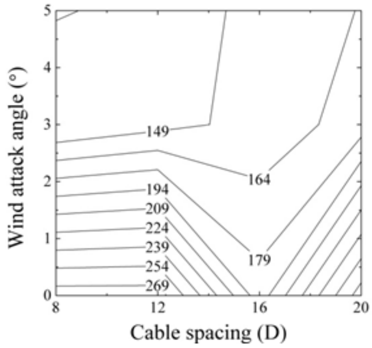

Fig. 9 First four mode shapes of the model cable

The modal frequencies of the model cable can be adjusted through its tensile force. Fig. 8 illustrates the variations of the modal frequencies with increasing tension force calculated from a finite element model. It is seen that when the tensile force is relatively small, the first vertical mode features an asymmetric mode shape with a frequency close to that of the second transverse mode (e.g., first asymmetric transverse mode), while the lowest frequency is for the first symmetric transverse mode. These modal characteristics are typical for sagging cables. When the tension force is sufficiently large, the first modes in both transverse and vertical directions are symmetric and the second modes are asymmetric. In this case, the cable can be modeled as a taut string with negligible sagging effect. For a taut string, the *i*-th modal frequency in vertical or transversal direction can be calculated as $f_i = \frac{i}{2L}\sqrt{\frac{gT}{W}}$, where $W$ is cable weight per unit length; $T$ is tensile force; $L$ is cable length; and $g$ is gravitational acceleration. This calculation gives the first two modal frequencies of the 1.095 and 2.190 Hz, which are very close to those obtained from the finite element model.

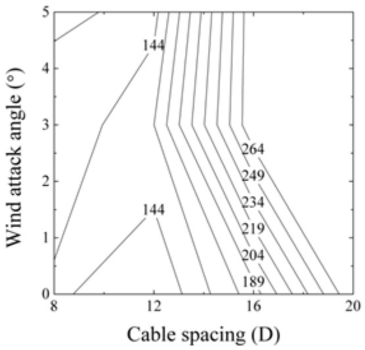
An adequate tensile force was selected to reduce the frequency ratio of the model cable to full-scale cable, so that the highest wind speed in wind tunnel meets the required design wind speed. The calculated and measured modal frequencies of the model cable under this specified tensile force are listed in Table 1. The modal shapes are displayed in Fig. 9. The first asymmetric modes in both transverse and vertical directions show very consistent characteristics of those of full-scale stay cable. The wake galloping generally follows an elliptical trajectory with coupled motion from both transverse and vertical oscillation modes having closed frequencies. In this study, the wake galloping vibration of the stay cable featuring asymmetric vertical and transverse modes is concerned. The frequency ratio of the model to the full-scale cable is 0.5(2.539+2.637)/2.199 = 1.177. According to the geometrical scale of 1 to 4.156, a wind speed ratio of 1 to 3.531 was calculated.



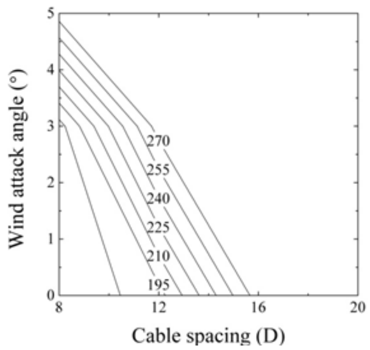

(a) Wind yaw angle of 0 degree




(b) Wind yaw angle of 10 degrees




(c) Wind yaw angle of 20 degrees




(d) Wind yaw angle of 30 degrees

Fig. 10 Critical reduced wind speed of wake galloping

In the wind tunnel wind speed range of 0 ~ 23 m/s, the Reynolds (Re) number of the model cable was 21400 ~ 32200. It is lower than the Re number of the full-scale stay cable with a range of 372000 ~ 557000. It is generally difficult to match Re number between the model and prototype in conventional wind tunnels. While the aerodynamics of circular cylinders are generally sensitive to Re number as it alters the separation points of the air flow in the cylinder surface, the characteristics of wake galloping of downstream cylinder is considered to be less sensitive to Re number (e.g., Ohya *et al.* 1989, Simiu and Scanlan 1996).

## 3. Test results of wake-galloping characteristics and analysis of data

A total of 48 testing cases concerning different cable spacing, wind yaw angle and angle of attack were conducted. The maximum wind speed in wind tunnel was 23 m/s, corresponding to a wind speed of 81 m/s in the full-scale bridge, which was higher than the verification wind speed of 71.4 m/s for this bridge. Fig. 10 illustrates the contour lines of the critical reduced wind speed of the wake galloping, expressed as functions of cable spacing and angle of attack at wind yaw angles

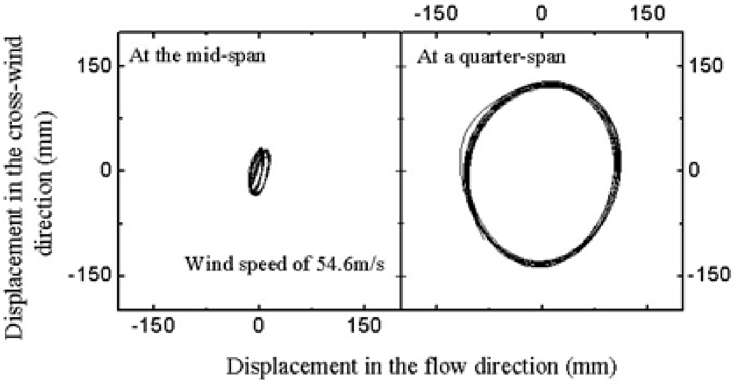


Fig. 11 Wake galloping trajectories of cables with a cable spacing of 16D, yaw angle of 10°, angle of attack of 5° and wind speed of 54.6 m/s

of 0, 10, 20 and 30 degrees. The critical wind speed is defined as the wind speed when the vibration amplitude of downstream cable reaches 1D. It should be noted in Fig. 10 that in the case where the wake galloping did not occur within the maximum testing wind speed range, the critical reduced wind speed is denoted as 277, i.e., the value at the maximum wind speed of 23 m/s in the wind tunnel. From these figures, we can see that the wake galloping phenomenon occurred in the majority of cases at wind speed less than 71.4 m/s, i.e., reduced wind speed of 244. It is noted that the critical reduced wind speed of wake galloping calculated by the approximate formula is $U_{cr} / fD = c\sqrt{S_c} = 80\sqrt{7.1} = 213$, which is very consistent to the results of this study with a zero wind yaw angle. There is argument that wake-galloping of parallel cables may not be well explained by reduced wind speed but real wind speed. The consistency in the critical reduced wind speed observed in this study as compared to the results in literature (e.g., Cooper 1985, Irwin 1997) suggests that the reduced wind speed can be used for determining the minimum wind speed above which wake galloping can be expected. It is worthy of further investigation on the adequacy of the reduced wind speed for explaining the amplitude of vibration.

Fig. 11 shows the vibration trajectories of wake galloping vibration of the downstream cable at mid-span and quarter-span locations at wind speed of 54.6 m/s (in full-scale bridge), spacing of 16D, yaw angle of 10°, and angle of attack of 5°. The vibration trajectories at other wind speed and other test cases are very similar but with different vibration amplitudes. The vibratory trajectory of wake galloping observed in the downstream cable was approximately an elliptical path, which consisting of the 1$^{st}$ asymmetric vertical mode and 1$^{st}$ asymmetric transverse mode. The vibration of downstream cable had no noticeable influence on the upstream cable, which is consistent with previous studies, in which rigid twin circular cylinder models were employed in wind tunnels (e.g., Brika and Laneville 1997). The upstream cable shows a negligible vibration. From the trajectory of the downstream cable it is seen that the amplitude in vertical vibration is only a little larger than that in transverse direction. It is different from the elliptical trajectory reported in previous studies where the transverse vibration is considerably larger. This difference may be related to the fact that the vertical motion is more sensitive to the variation of cable tension in the vibration with large amplitude. In the cable vibration, the tension is changed. The tension of the cable model is not very high, so it is more sensitive to the variation of cable tension. The tension variation may have different influences on the modal frequencies and shapes in the transverse and vertical directions. However, the tension of the full-scale stay cable is relatively high, so it has opposite situation to the model cable. Moreover, the length of the cable model in the test was limited, so the boundary effect could also have some influence.

By comparing the characteristics of wake galloping at different cable spacing, it is clear that the cable spacing is an important factor affecting critical reduced wind speed of wake galloping of parallel stay cables. The critical wind speed decreases with decreasing cable spacing in the range between 8D and 12D. However, previous research revealed that the most adverse cable spacing is in the range between 8D and 20D (e.g., Tanaka 2003). In these tests, the lowest critical reduced wind speed of wake galloping occurred at the wind yaw angle of 0°, the wind attack angle of 0°, and the separation of 8D. The wind velocity in wind tunnel is 11.8 m/s, corresponding to the wind speed of 41.7 m/s in the full-scale bridge.

This wind tunnel study simulated the action of flow in different direction on parallel cables in three dimensions by changing the yaw angle of wind, which is different from tests employing ideal rigid parallel cylinders. From the test results (Fig. 10), we can conclude that the cases with yaw angle in the range between 10° and 20° are the most adverse conditions with lower critical wind speed for wake galloping. The existence of yaw angle changes the cross section of the upstream cable in flow direction (not circular cross section any more), and there are not only transverse component but also axial component of gap flow acting on the cables. Consequently, the mechanism of aerodynamic interaction between parallel cables is more complicated.

It was observed that wake galloping was relatively sensitive to wind attack angle when the yaw angle was small, and was more easily excited with a large angle of attack. This is primarily due to the distribution of wake unstable region caused by the circular cross section of upstream cable on the either side of the cross section along the flow-direction axis, as shown in Fig. 1. When the separation is small, the departure of the unstable region is small; when the separation is far, the departure is large. The relative variations in the unstable region may enable the downstream cable, which is originally not in this region, to enter it through change of the angle of attack. Consequently wake galloping occurs.

## 4. Measures to suppress wake galloping

Mechanical measures to suppress the wake galloping of cables include the installation of a

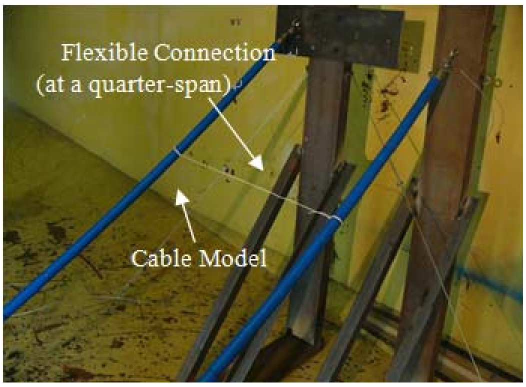



Fig. 12 A means of suppressing vibration (flexible connection, at a quarter-span)

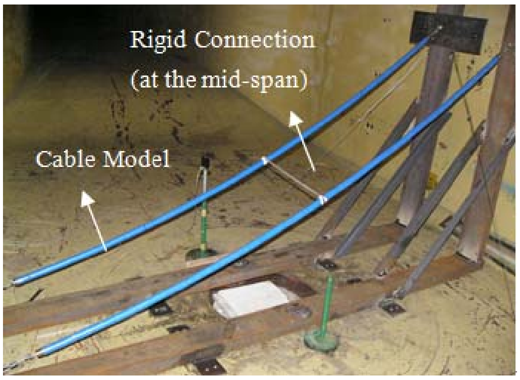



Fig. 13 A means of suppressing vibration (rigid connection, at the mid-span)

Table 2 Influence of cable connection on the critical wind speeds of cable wake galloping

| No. | Connection | Spacing | Connection position | *Ucr* (m/s) in wind tunnel | *Ucr* (m/s) in full-scale bridge |
|---|---|---|---|---|---|
| 1 | Flexible | 8D | no connection | 13.7 | 44.0 |
| 2 | | | L/2 | 11.2 | 36.0 |
| 3 | | | L/4, 3L/4 | 14.4 | 46.3 |
| 4 | | 12D | no connection | 13.1 | 42.1 |
| 5 | | | L/2 | 10.1 | 32.4 |
| 6 | | | L/4, 3L/4 | 11.3 | 36.3 |
| 7 | | 16D | no connection | 13.8 | 44.3 |
| 8 | | | L/2 | 12.8 | 41.1 |
| 9 | | | L/4, 3L/4 | No Galloping | — — |
| 10 | | 20D | no connection | 15.0 | 48.2 |
| 11 | | | L/2 | No Galloping | — — |
| 12 | | | L/4, 3L/4 | No Gapploing | — — |
| 13 | Rigid | 8D | no connection | 13.7 | 44.0 |
| 14 | | | L/2 | 16.7 | 53.6 |
| 15 | | | L/4, 3L/4 | No Galloping | — — |
| 16 | | 12D | no connection | 13.1 | 42.1 |
| 17 | | | L/2 | 14.2 | 45.6 |
| 18 | | | L/4, 3L/4 | No Galloping | — — |
| 19 | | 16D | no connection | 13.8 | 44.3 |
| 20 | | | L/2 | No Galloping | — — |
| 21 | | | L/4, 3L/4 | No Galloping | — — |
| 22 | | 20D | no connection | 15.0 | 48.2 |
| 23 | | | L/2 | No Galloping | — — |
| 24 | | | L/4, 3L/4 | No Galloping | — — |

transversely connected cable system and the use of additional damping devices. It was reported that the wake galloping could be suppressed at the modal damping ratio of 0.8% (a logarithmic decrement of 0.05) or higher (Miyata 1991, Narita and Yokoyama 1991). In the case of very long stay cables, it will be difficult to increase the damping ratio by damping devices. In addition, the lifetime of additional damping devices is relatively short. On the other hand, as the upstream cable was nearly stable when the wake galloping with large amplitude occurred in the downstream cable, installation of connections between two cables will provide vibration transfer from downstream cable to upstream cable and thus result in suppression of wake galloping.

To examine the effectiveness of cable connection for suppressing wake galloping, the most susceptible case with the yaw angle of 10° and angle of attack of 5° was considered. Two types of cable connections, i.e., flexible and rigid connections, and two positions, i.e., mid-span (L/2), and quarter-span (L/4 and 3L/4), thus a total of four types of arrangements of cable connection were investigated. In the case of flexible connection (Fig. 12), the connection cable can not elongate but can shorten. Table 2 listed the critical wind speed of wake galloping for different types of connections. In the case of flexible connection, when the cable spacing is 8D or 12D, the wake galloping occurred at even a lower wind speed. On the other hand, when the cable spacing is 16D or 20D, the flexible connection at L/4 and 3L/4 can completely eliminate wake galloping. It is observed that the rigid connection at L/4 and 3L/4 was effective in suppressing wake galloping of the downstream cables for the cable spacing from 8D to 20D.

It should be noted that a flexibly-connected cable system is not an ideal method to suppress wake-galloping of closely-spaced parallel stay cables. The use of rigidly-connected cable systems (Fig. 13) can be more effective, especially connections at multiple locations are implemented. It should also be emphasized that use of aerodynamic measures to change the wake flow could lead to more effective suppressions of wake-galloping; however this is beyond the scope of this study.

## 5. Conclusions

The wake galloping characteristics of parallel three-dimensional stay cables under a complex wind environment can be different from that of ideal rigid twin circular cylinders observed in wind tunnel. Aerodynamic interaction between parallel cables in the full-scale bridge has obvious three-dimensional features. The comprehensive experimental investigation using aeroelastic cable models under different conditions presented in this study, gives new insights into wake galloping of parallel stay cables. It was observed that wake galloping is sensitive to the angle of attack. Cables with a yaw angle of around 10 to 20 degrees are most susceptible to wake galloping. As expected, the wake galloping becomes less susceptible when the spacing increases. Use of rigid connections of cables at multiple locations can effectively lead to vibration energy transfer and result in suppression of wake galloping. It should be emphasized that, in addition to this mechanical measure, use of aerodynamic measures to change the wake flow and the aerodynamic characteristics of cables could also provide alternative effective means for suppressing wake galloping of parallel stay cables.

## References

Brika, D. and Laneville, A. (1997), "Wake interference between two circular cylinders", *J. Wind Eng. Ind. Aerod.*, **72**(11-12), 61-70.

Cooper, K.R. and Wardlaw, R.L. (1971), "Aeroelastic instabilities in wakes", *Proceedings of the International Conference on Wind effects on Buildings and Structures,* Tokyo, Japan.

Cooper, K.R. (1985), *A note on the wind-induced vibrations of bundled bridge stay cables*, National

Research Council of Canada, Note provided to RWDI.
Gu, Z. and Sun, T. (1999), "On interference between two circular cylinders in staggered arrangement at high subcritical Reynolds numbers", *J. Wind Eng. Ind. Aerod.*, **80**(3), 287-309.
Hata, K., Kusuhara, S. and Nanai, T. (2004), "A study on countermeasures for wake galloping in parallel cables of cable-stayed bridges", *Proceedings of the 18th National Engineering Symposium*, (In Japanese)
Hu, J.H. and Zhao, Y.Y. (2006), "Wind tunnel studies on the behaviour of aeroelastic twin cable model", *J. Dyn. Control*, **4**(2), 179-186. (in Chinese)
Irwin, P.A. (1997), "Wind vibrations of cables on cable-stayed bridges", *Proceedings of the Structural Congress XV*, Portland, Oregon.
Kumarasena, S., Jones, N.P., Irwin, P. and Taylor, P. (2005), *Wind induced vibration of stay cables (Interim Final Report)*, RI 98-034, RDT 05-004.
Maeda, H., Kubo, Y., Kato, K. and Fukushima, S. (1997), "Aerodynamic characteristics of closely and rigidly connected cables for cable-stayed bridges", *J. Wind Eng. Ind. Aerod.*, **69-71**, 263-278.
Miyata, T. (1991), "Design consideration for wind effects on long-span cable-stayed bridges", (Eds. Ito, M. *et al.*), *Cable-stayed bridges: Recent developments and their future*, Tokyo, Elsevier Science Publishers B.V., 235-256.
Miyata, T., Yamada, H. and Katsuchi, H. (2004), "Wake-induced flutter of twin cables and its countermeasure", *Proceedings of the 5th International Colloquium on Bluff Body Aerodynamics and Applications,* Ottawa, Canada.
Narita, N. and Yokoyama, K. (1991), "A summarized account of damping capacity and measures against wind action in cable-stayed bridges in Japan", (Eds. Ito, M. *et al.*), *Cable-stayed bridges: Recent developments and their future*, Tokyo, Elsevier Science Publishers B.V., 257-278.
Ohya, Y., Okajima, A. and Hayashi, M. (1989), "Wake interference and vortex shedding", in: (Ed. N. Cheremisinoff), *Encyclopedia of Fluid Mechanics*, 323-389.
PTI Guide Specification (2001), *Recommendations for stay cable design, testing and installation,* Post-Tensioning Institute Committee on Cable-Stayed Bridges, (4th Ed.)
Simiu, P.D. and Scanlan, R.H. (1996), *Wind effects on structures*, (3rd Ed.), John Wiley & Sons, New York, 1996.
Tanaka, H. (2003), "Aerodynamics of cables", *Fifth International Symposium on Cable Dynamics*, 11-21.
Tokoro, S. and Komatsu, H. (2000), "A study on wake-galloping employing full aeroelastic twin cable mode", *J. Wind Eng. Ind. Aerod.*, **88**(2-3), 247-261.
Williams, R.G. and Suaris, W. (2006), "An analytical approach to wake interference effects on circular cylindrical structures", *J. Sound Vib.*, **295**(1-2), 266-281.
Xu, A.J., Hao, C. and Li, Y.L. (2005), "Aerodynamic problems of cables", *World Bridges*, **4**, 34-37. (In Chinese)
Zdravkovich, M.M. and Pridden, D.L. (1977), "Interference between two circular cylinders; series of unexpected discontinuities", *J. Wind Eng. Ind. Aerod.*, **2**(3), 255-270.
Zdravkovich, M.M. (1977), "Review of flow interference between two circular cylinders in various arrangement", *J. Fluids Eng.*, **99**(4), 618-633.
Zdravkovich, M.M. (1987), "The effects of interference between circular cylinders in cross flow", *J. Fluid Struct.*, **1**(2), 239-261.
Zdravkovich, M.M. (1988), "Review of interference-induced oscillations in flow past two parallel circular cylinders in various arrangements", *J. Wind Eng. Ind. Aerod.*, **28**(1-3), 183-199.

*J H*