

# Aerodynamic problems of cable-stayed bridges spanning over one thousand meters

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**Abstract:** The elongating of cable-stayed bridge brings a series of aerodynamic problems. First of all, geometric nonlinear effect of extreme long cable is much more significant for cable-stayed bridge spanning over one thousand meters. Lateral static wind load will generate additional displacement of long cables, which causes the decrease of supporting rigidity of the whole bridge and the change of dynamic properties. Wind load, being the controlling load in the design of cable-stayed bridge, is a critical problem and needs to be solved. Meanwhile, research on suitable system between pylon and deck indicates fixed-fixed connection system is an effective way for improvement performance of cable-stayed bridges under longitudinal wind load. In order to obtain aerodynamic parameters of cable-stayed bridge spanning over one thousand meters, identification method for flutter derivatives of full bridge aero-elastic model is developed in this paper. Furthermore, vortex induced vibration and Reynolds number effect are detailed discussed.

**Key words:** cable-stayed bridge; dynamic properties; suitable system between pylon and deck; Reynolds number effect; flutter derivatives

## 1 Introduction

At the end of 20 century, the design and construction technology have made great improvement. As far as cable-stayed bridge is concerned, in 1999, Tatara Bridge is the longest bridge in the world, which has main span of 890 m. The second longest bridge is Nor-

mandy Bridge in France with main span 856 m. Meanwhile, in the last 20 years, bridge technology in China has made remarkable progress as well, which is newly promoted by Sutong Bridge and Stonecutter Bridge. In 2008, the open of Sutong Bridge, the longest bridge in the world, with the span of 1 088 m, became a new milestone in the development of cable-stayed bridge.

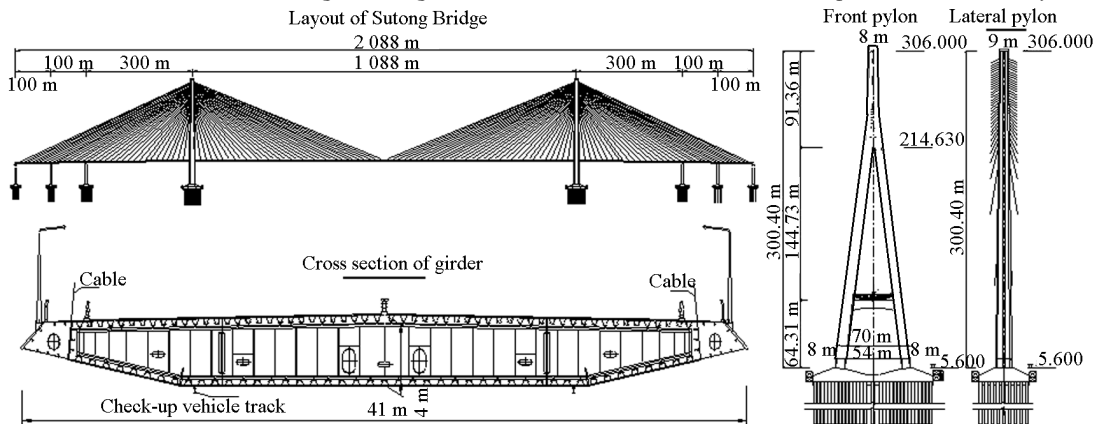


Fig. 1 Plan, cross section of girder and pylon of Sutong Bridge

For long span cable-stayed bridge spanning over one thousand meters, characters of structure and wind environment make wind effect much more sensitive and important. Wind loading becomes the controlling design factor. Besides, refined research should be car-

ried out on structure dynamics and aerodynamic coefficients of major components, such as pylon, girder and cables to guarantee economy of structure design. Meanwhile, to make sure the safety of structure, avoid fatigue destroy, safety and amenity of driving vehicle

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on deck, it is quite essential to solve a series of problems, such as flutter stability of deck, gallop stability of pylon, response of vortex induced vibration and buffeting, vibration and mitigation of super long cable, rain vibration and parameter vibration of cables and safety of driving vehicle.

In this paper, several aerodynamic problems during the design and construction process of Sutong Bridge will be discussed, such as dynamic properties of super long cable-stayed bridge, wind load of components, suitable system under longitudinal wind load, flutter derivatives identification based on full bridge aero-elastic model and high Reynolds number effect on wind load and wind induced vibration.

## 2 Analysis and research for dynamics of super long cable-stayed bridge<sup>[1]</sup>

As we know, with the increasing of span, dynamic properties of super long cable-stayed bridge will decrease. Meanwhile, under static wind load, they will change significantly as well. As is shown in Fig. 2, under the static wind load, lateral displacement of cable and corresponding geometric nonlinear effect cause significant change of vertical supporting rigidity of super long cable-stayed bridge.

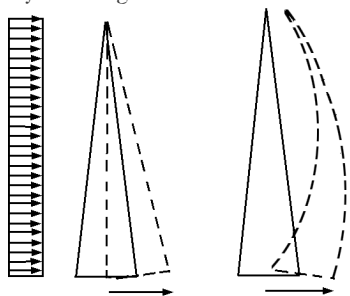


Fig. 2 Illustration for nonlinear effect of cable lateral displacement

Research results show that, considering the static wind load on cables, equivalent elastic modulus of stay cables quickly decreases with the increasing of wind speed. At the wind speed of 100 m/s, equivalent elastic modulus of the longest cable decreases 50 % compared with zero wind speed. Therefore, decrease of elastic modulus caused by lateral wind cannot be ignored. However, for the cables with small inclination, it would not be so significant. In summary, the larger the inclination of cable is, the higher the wind speed is, and the more the equivalent elastic modulus decreases (Fig. 3).

Under the static wind load, dynamic properties change with the increase of wind speed. It is necessary to improve the simulation of cable. During the research on Sutong Bridge, model of multi-element cable simu-

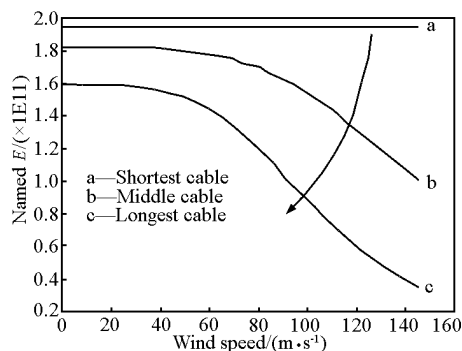


Fig. 3 Decrease of elastic modulus for cable of Sutong Bridge under lateral static wind load

lation (MECS)<sup>[2]</sup> was developed, which means simulating the cable with multiple elements. Compared with traditional method one element cable simulation (OECS), in which Ernst formula is used to modify the elastic modulus of one element cable, MECS can simulate the character of the vibration with its deformation.

OECS and MECS are compared in dynamic property analysis of Sutong Bridge under lateral wind loading. It is shown that with the increasing of wind speed, frequencies of symmetric vertical bending and asymmetric vertical bending calculated by MECS decrease, which OECS cannot predict. The reason is that MECS can reveal geometric nonlinear effect on vertical rigidity induced by lateral wind load, as is shown in Fig. 4. Meanwhile, the results obtained by full bridge aero-elastic model test are in accord with those obtained by MECS, shown in Fig. 5.

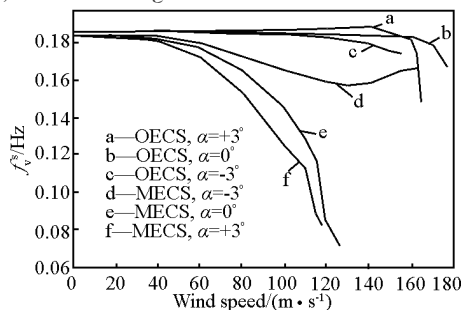
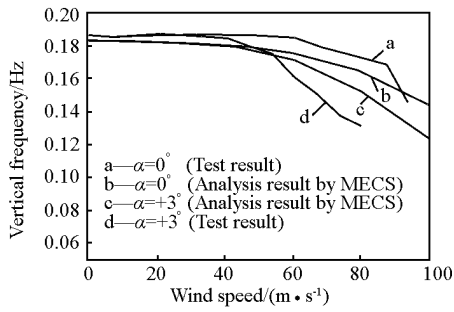


Fig. 4 Frequency of first step of vertical bending vibration mode vs. wind speed (OECS vs. MECS)

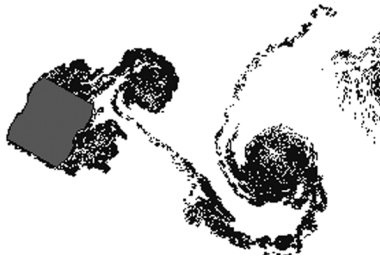
## 3 Analysis on wind load of super long cable-stayed bridge

Wind loading on long span cable-stayed bridge can be divided into loading on pylons, deck and cables. During the design of Sutong Bridge, the wind load on pylons of Sutong Bridge is obtained by CFD (computation fluid dynamic) technique<sup>[3]</sup>. In this method, discrete vortex numerical method<sup>[3]</sup> is used to solve the distribution of vortices field and velocity

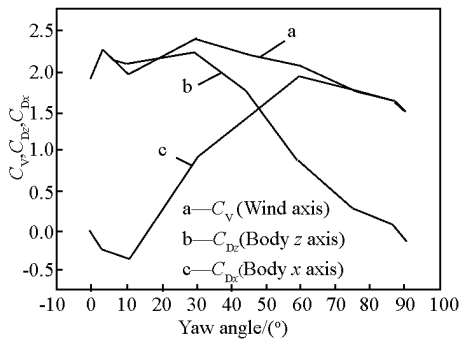


**Fig. 5 Comparison of frequency of vertical bending between aero-elastic model test and MECS**

field, and aerodynamic force on cross section of girder can be obtained according to the theory of vortex dynamics. Through CFD technique, drag coefficients and lift coefficients of tower columns on windward and leeward can be obtained. Research shows that maximum wind load on pylon does not appear on the yaw angle of 0° or 90°, but on a certain yaw angle, such as 45° or 60°. Fig. 6 shows the flow field distribution of upper pylon column, and Fig. 7 shows the simulation results of pylon drag coefficients.



**Fig. 6 Flow field distribution of upper pylon column of Sutong Bridge**



**Fig. 7 Drag coefficient of upper pylon column of Sutong Bridge**

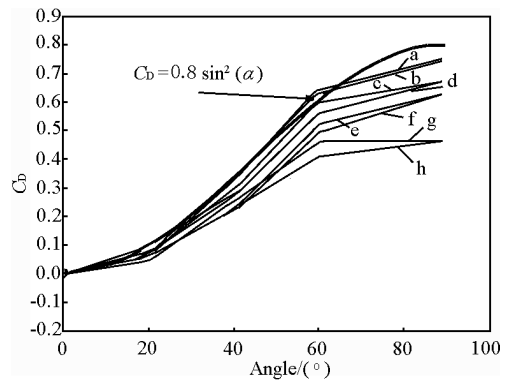
Thin box girder and dense cable system are usually adopted in long span cable-stayed bridge. With the increase of span, the effect of wind load grows synchronously, while the proportion of the wind load on cable and girder gradually grows. Wind load on cables might be larger than that on girder. Therefore, for long span cable-stayed bridge, it is significant important to mini-

mize the wind load on cables to the lowest level.

During the design process of Sutong Bridge, wind tunnel test combined with CFD is applied to study wind loading on stay cables. In the wind tunnel test, wind loads of cable on longitudinal direction and lateral direction are calibrated by force balance, shown in Fig. 8. A series of force-measurement tests on all types of cables are carried out and the relationship between wind load drag coefficients of cable and inclinations was obtained, shown in Fig. 9.



**Fig. 8 1:1 model test for force measurement of Sutong Bridge**

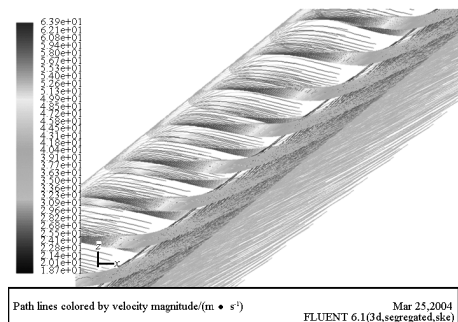


a—4 mm surface with helix line,negative elevation angle;  
b—4 mm surface with helix line,positive elevation angle;  
c—2 mm surface with helix line,positive elevation angle;  
d—2 mm surface with helix line,negative elevation angle;  
e—Surface with pit on,positive elevation angle;  
f—Surface with pit on,negative elevation angle;  
g—Smooth surface,positive elevation angle;  
h—Smooth surface,negative elevation angle

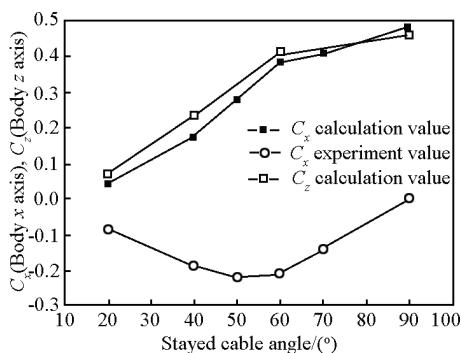
**Fig. 9 Result of force measurement for cable wind load**

For further verification of the result obtained wind tunnel test, CFD analysis is adopted for a trial condition and its result matches the wind tunnel test. Meanwhile, CFD analysis reveals many phenomena and conclusions which could not be obtained by wind tunnel test, such as lift coefficient of cable and three-dimension flow of cable. Apparently, the combination of CFD and wind tunnel test would be much more effective. CFD simulation for three-dimension flow of cable

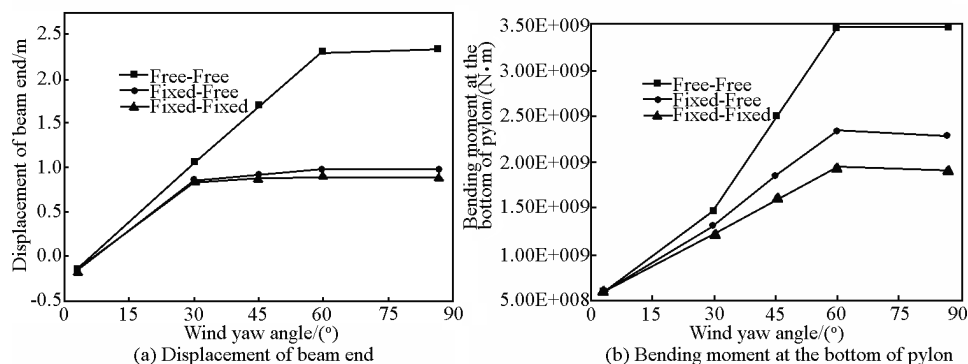
is shown in Fig. 10, and comparison of wind load of cable between wind tunnel test and CFD is shown in Fig. 11.



**Fig. 10** CFD simulation for three-dimension flow of cable



**Fig. 11** Comparison of wind load of cable between wind tunnel test and CFD



**Fig. 12** Comparison of along wind load of different connecting systems

Research also shows that among the three connection systems, Fixed-Fixed is the most effective type and could effectively reduce the longitudinal wind load.

#### 4 Research on suitable system for super long cable-stayed bridge under wind load

Wind load could be highly affected by the structure system. Even in the same condition, different structure systems own different wind effect. For Sutong Bridge, in order to reduce wind load, it is quite important of choosing the suitable system. To analyze the effect of different structure systems on internal force and displacement, three different connection systems of pylon and girder are discussed, including Free-Free, Fixed-Free and Fixed-Fixed, where Free means floating constraint and Fixed means limit constraint. For the difference of the three structure systems is the constraint between pylon and girder, major effect would attach on the internal force and displacement of girder and pylon.

Structure response of the wind load on different yaw angles indicates, in the condition of the whole bridge heating, the type of Fixed-Fixed could effectively constrain the longitudinal displacement of girder and a part of the load of girder transfers to the top of pylon by the cables, the other part transfers by the connection system without cables the path of which is much shorter, and makes bending moment of pylon on the bottom decrease. In the condition of no heating, Fixed-Fixed also is slightly better than Fixed-Free and both of them are apparently better than Free-Free. Besides, with the increasing of yaw angle, longitudinal constraint system shows more and more significant effect, for it does no matter with the lateral wind load, shown in Fig. 12.

Accordingly, Fixed-Fixed can be suggested as the suitable system to reduce the wind load of pylon of super long cable stayed bridge, which is applied in Sutong Bridge.

## 5 Recognition of aerodynamic parameter for aero-elastic model

In order to invest the nonlinear effect of super long cable-stayed bridge under wind load, during the research and design of Sutong Bridge, recognition method for flutter derivatives based on full bridge aero-elastic model is developed. The principle of this method is as below:

If aero-elastic model owns  $N$  steps of vibration modes, for undamped structure, free vibration equation is:

$$[M]\ddot{X} + [K]_s X = 0 \quad (1)$$

motion equation can be expressed as the form of mode coordinate,

$$[m]\ddot{q} + [k]q = 0 \quad (2)$$

Where,  $[m] = \text{diag}(m_{ii}) (i = 1, 2, \dots, N)$ ,

$[k] = \text{diag}(k_{ii}) (i = 1, 2, \dots, N)$

For the structure damp and common condition,

$$[m]\ddot{q} + [r]\dot{q} + [k]q = 0 \quad (3)$$

Where,  $[r] \in R^{N \times N}$ . Meanwhile, self-excitation force model<sup>[4]</sup> was established according to 18 flutter derivatives, so

$$\begin{aligned} \overline{F_{ij}}(x) &= \int_0^L F_{ij}(x) \phi_i(x) dx \\ &= \int_0^L [A_{ij}^{(1)} \dot{q}_j + A_{ij}^{(2)} q_j] \phi_j(x) \phi_i(x) dx \\ &= A_{ij}^{(1)} \dot{q}_j \int_0^L \phi_j(x) \phi_i(x) dx + \\ &\quad A_{ij}^{(2)} q_j \int_0^L \phi_j(x) \phi_i(x) dx \end{aligned} \quad (4)$$

$$[m]\{\ddot{q}\} + [r]\{\dot{q}\} + [k]\{q\} = [\overline{F_{ij}}]_{N \times N} = [A_{ij}^{(1)}]_{N \times N} \{\dot{q}\} + [A_{ij}^{(2)}]_{N \times N} \{q\} \quad (5)$$

$$\begin{aligned} [m]\{\ddot{q}\} + ([r] - [A_{ij}^{(1)}])\{\dot{q}\} + \\ ([k] - [A_{ij}^{(2)}])\{q\} = 0 \end{aligned} \quad (6)$$

During recognition, ERA (eigenvalue realization algorithm) character system is used to obtain rigidity matrix and damp matrix of structure, and flutter derivatives of girder cross section can be got. In this paper, flutter derivatives of aero-elastic model obtained with this method. Flutter derivatives of aero-elastic model and segmental model are shown in Fig. 13.

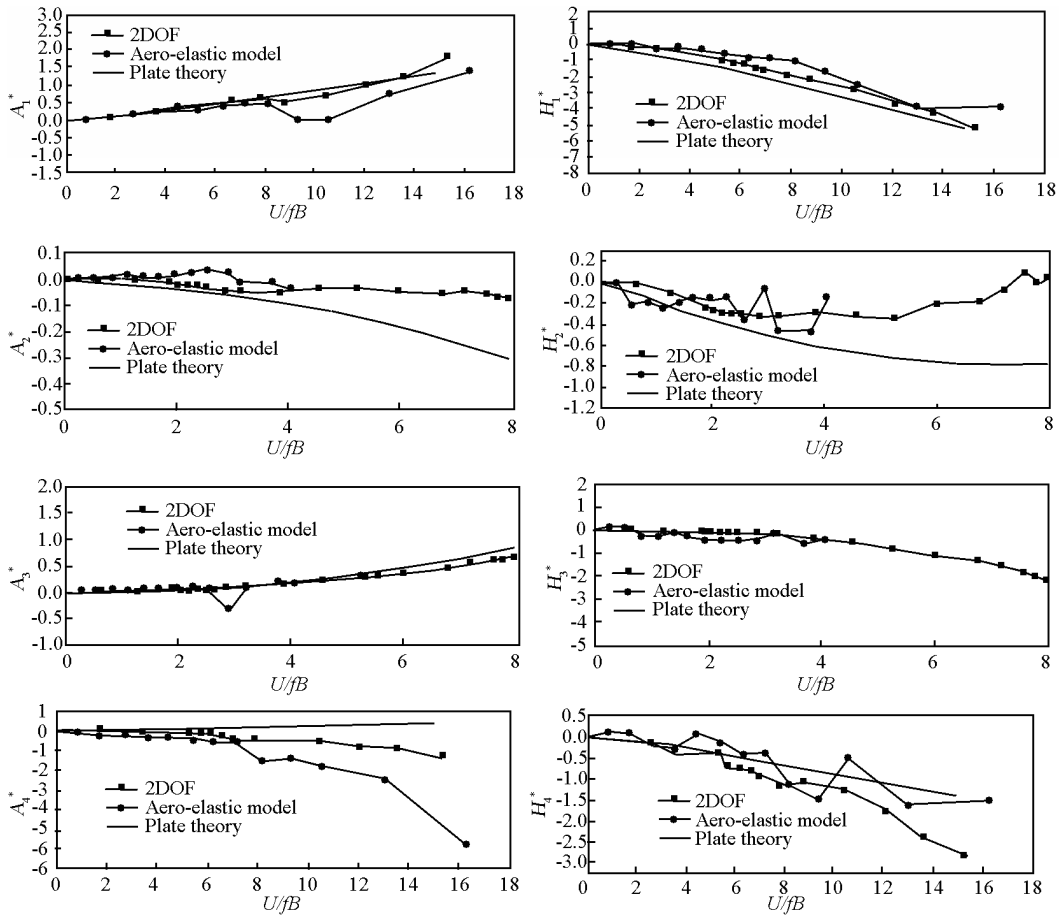


Fig. 13 Comparison for result of aero-elastic model, segmental model and plate theory (Flutter Derivatives  $A_i^*$ ,  $H_i^*$ ,  $i = 1, 2, 3, 4$ )

## 6 Research of high Reynolds number effect on wind load and wind induced vibration

For super long cable-stayed bridge, vortex induced vibration of girder will cause parameter vibration and fatigue. In order to avoid or mitigate vortex induced vibration, study on vortex induced vibration of girder and high Reynolds number effect is needed during design step.

For original design scheme, vortex induced vibration appears in segment model test. Although its amplitude do not exceed limit, in order to mitigate vortex induced vibration, a series of measurements were tested, shown in Fig. 14<sup>[5]</sup>.

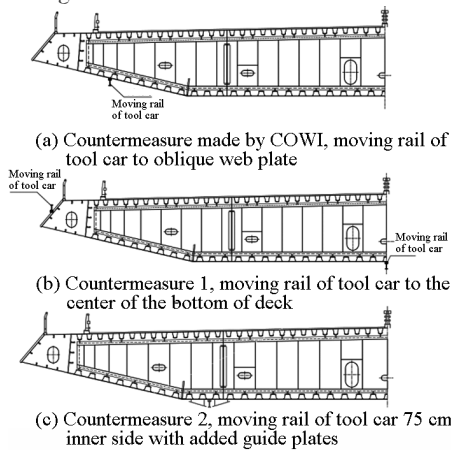


Fig. 14 Countermeasures to mitigate vortex induced vibration

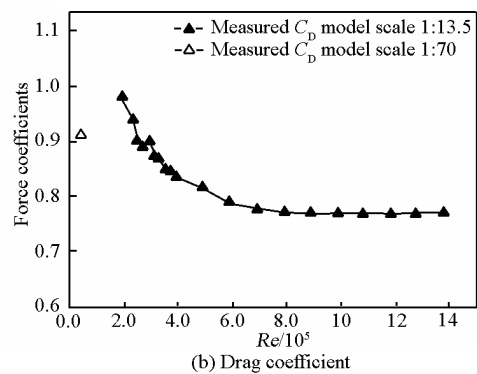
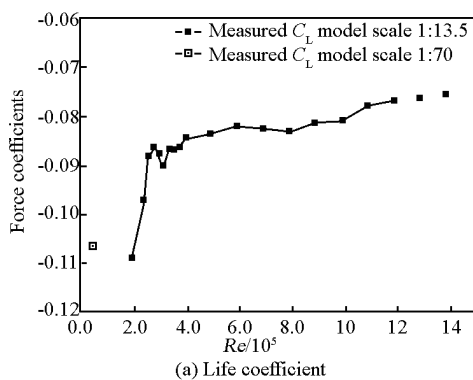


Fig. 16 Reynolds number effect of aerodynamic coefficient at completed status of the bridge on attack angle of  $0^\circ$

## 7 Conclusion

In this paper, several critical aerodynamic prob-

lems during wind resistance design of Sutong Bridge are discussed. Research shows, super long cable-stayed bridge is different from common cable-stayed bridge in

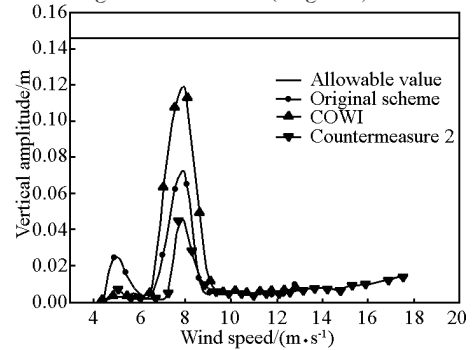


Fig. 15 Amplitudes of vortex excited vibration of Sutong Bridge ( $\alpha = 0^\circ$ , smooth flow)

Moreover, change of Reynolds number will affect the wind load on girder, shown in Fig. 16. The result of test shows that Reynolds number effect of girder is quite remarkable, especially for drag coefficient.

For cable-stayed bridge spanning over one thousand meters, Reynolds number effect of girder shall be sufficiently studied. The possibility of vortex induced vibration and measurements of amplitude mitigation needed to be analyzed, which is a critical aerodynamic problem for cable stayed bridge spanning over one thousand meters.

many aspects, such as dynamics, wind load, Reynolds number effect and connection system of pylon and girder. Some thought and solution are developed in this paper. However, many other aerodynamic problems of cable-stayed bridge spanning over one thousand meters still need further study, such as rain vibration of cable, aerodynamic instability and so on.

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