The 2016 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM16)
Jeju Island, Korea, August 28-September 1, 2016

Effect of Guide Vane beside the Maintenance Rail on Vortex-Induced Vibration of Streamlined Box Girder

*Jun Liu[1], Haili Liao[2], Mingshui Li[3], Jiawei Wan[4]

[1), 2), 3), 4)] *Research Center for Wind Engineering, SWJTU, Chengdu 610031, China*
[1)] *liu.jun@my.swjtu.edu.cn*

ABSTRACT

In order to study the vortex-induced vibration performance of streamlined box girder and seek effective mitigation measures, a long span cable-stayed bridge with steel-box girder was taken as an example to investigate the vortex-induced vibration of the main girder through section model wind tunnel tests at a scale of 1:50. The two-dimensional flow field around the cross section of the main girder was modeled by computational fluid dynamics numerical simulation. The results show that alternate vortexes formation and shedding are repeated periodically behind the maintenance rails, which means that the rails have a significant impact on the vortex-induced vibration. The root mean square value of lift coefficient has a 24% reduction when the guide vanes move from the outside to the inside of the maintenance rails, implying that the vortex-induced vibration can be effectively mitigated by setting guide vane inside the maintenance rail.

1. INTRODUCTION

The increase in span length of long span bridges results in a noteworthy decrease in their stiffnesses and dampings. This denotes that long span bridges are susceptive to the wind load effects. Wind induced vibration is one of the most critical issues to be addressed in long span bridge design and construction (Xu et al. 2009; Larsen et al. 2008). Vortex-induced vibration is one of the most common wind induced vibrations and it is easy for long span bridges to occur at the relative low wind speed. While the vortex-induced vibration does not cause catastrophic damage to long span bridges as flutter, it can affect the comfort and safety of moving vehicles and pedestrians (Xian et al. 2008; Xian et al. 2009). Hence, vortex-induced vibration suppression measures are of great importance to long

[1)] Graduate Student
[2)] Professor
[3)] Professor
[4)] Graduate Student

span bridges.

There are a lot of vortex-induced vibration suppression measures, which are mainly divided into structural measures and aerodynamic measures. The structural measures mostly include enlarging structural masses, stiffnesses and dampings. Meanwhile, the aerodynamic measures consist of guide vanes, fairings, stabilizers, and so on (Liu 1995; Sun et al. 2012). Because of the simple structure, low cost and efficient vibration suppression, aerodynamic measures have become the preferred measure to restrain vortex-induced vibration of long span bridges.

For different cross section forms of bridge girder, the aerodynamic performances are significantly different as well as the vortex-induced vibration suppression measures (Sarwar et al. 2010). Previous wind tunnel experimental results have shown that optimizing the location of maintenance rails can effectively suppress the vortex-induced vibration of the long span bridge with steel-box girder (Li et al. 2011). Experimental studies have also shown that the inside deflector of the maintenance rail can mitigate the vertical vibration while the outside deflector can reduce the wind speed range of the torsion vortex-induced vibration of streamlined box girder (Zhu et al. 2015). The conclusions above were obtained based on a series of wind tunnel test which is the main research method for vibration mitigation measures. And the design of optimization measures is potentially of subjectivity and blindness.

In this paper, wind tunnel test and Computational Fluid Dynamics (CFD) were combined in the study of vortex-induced vibration suppression measures. A long span cable-stayed bridge with steel-box girder was taken as an example and the vortex-induced vibration of the main girder was investigated through section model wind tunnel tests at a scale of 1:50. Furthermore, a two-dimensional numerical model of the main girder was established and analyzed by CFD numerical simulation and the results show that the maintenance rail is the key factor to induce the vortex-induced vibration. Series of optimized measures centering on the maintenance rail were designed and test through wind tunnel tests. The results demonstrate the angled guide vane set inside the maintenance rail can effectively mitigate the vortex-induced vibration. Vortex-induced vibration is one of the most common wind induced vibrations and it can affect the comfort and safety of vehicles and pedestrians. The traditional research method for vibration mitigation measures is wind tunnel test (Xu et al. 2009), which is both time consuming and expensive. In this paper, Computational Fluid Dynamics and wind tunnel test were combined in the study of vortex-induced vibration suppression measures.

2. Dynamic characteristic analysis

The cable-stayed bridge, selected as the study issue, has double pylons and double cable planes and the main span is 608 m, as shown in Fig. 1. The computation model of the bridge structure is created by using three dimensional finite element methods. The steel-box girder, pylons and piers are simulated with beam elements, the cables are simulated with link elements, the secondary dead loads are simulated with mass elements. The boundary conditions are applied according to the actual constraints of the bridge structure. The dynamic characteristics of the structure, which provides the basis for the wind tunnel test, are calculated by ANSYS finite element procedure. As shown in Tab. 1 and Fig.3, the structural natural frequencies and mode features are obtained.

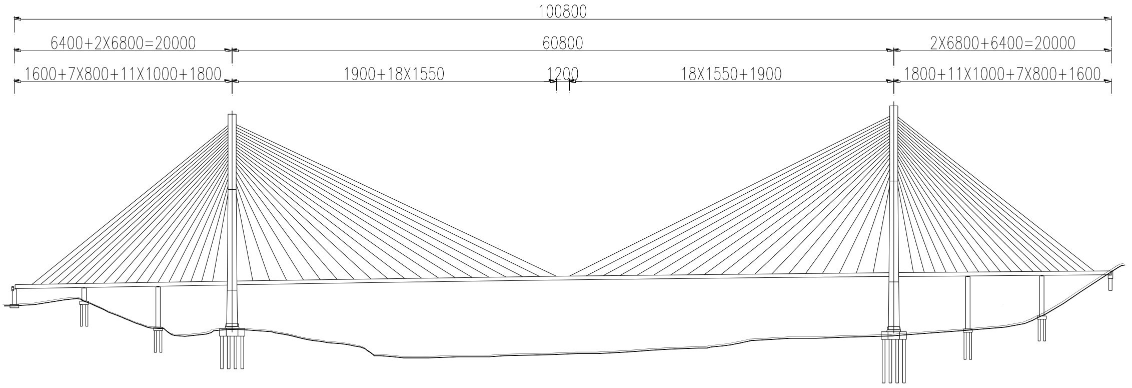


Fig. 1 Arrangement of the bridge (unit: cm)

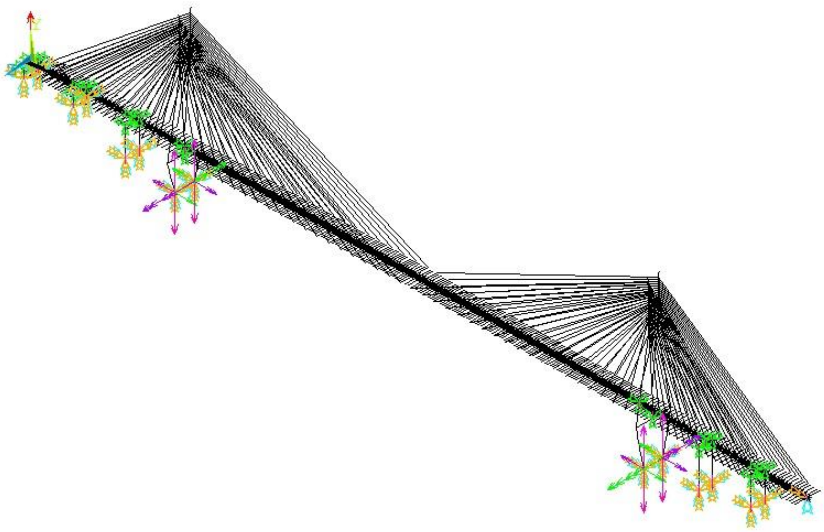
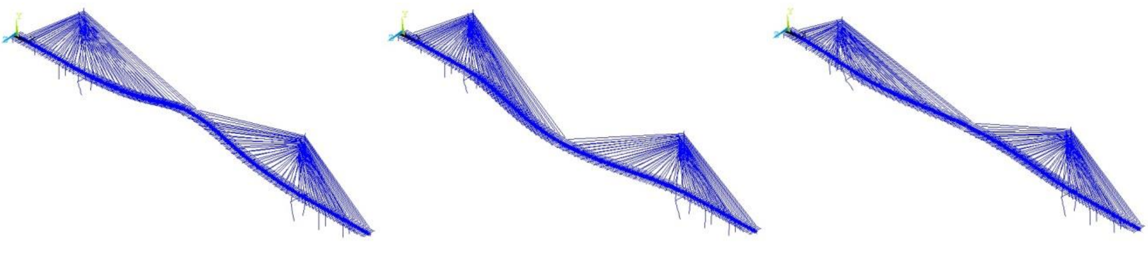


Fig. 2 Three-dimensional finite element model of the bridge



(a) Lateral bending vibration (b) Vertical bending vibration (c) Torsional vibration

Fig. 3 Main mode features of the bridge

Tab. 1 Structural natural frequencies and mode features

Mode feature	Natural frequency (Hz)
First symmetric vertical bending vibration	0.2922
First symmetric lateral bending vibration	0.3422
First antisymmetric vertical bending vibration	0.3836
First symmetric torsional vibration	0.5607
First antisymmetric torsional vibration	0.8227

3. VORTEX-INDUCED VIBRATION TEST

According to the streamlined box girder of a long span bridge (Fig. 4), the section model in completed bridge stage was designed and manufactured at a scale of 1:50 and the main test parameters is proportional with the actual bridge (Tab. 2).

The tests were carried out in an industrial wind tunnel (type: XNJD-1) of Southwest Jiaotong University, which is a closed circuit wind tunnel with two tandem closed test sections. The second test section, 2.4m (width) × 2.0m (height) × 16.0m (length), was used. As shown in Fig. 5, the model is elastically mounted in wind tunnel by 8 coil springs through two metal support arms, and the model may move in vertical and torsional directions but the motion in along wind direction is restrained by steel wires. The displacements of the model at upstream and downstream locations are measured by two laser displacement transducers. The test is conducted in smooth oncoming flow, turbulent intensity~0.5%, wind attack angle ~3º, 0º and -3º. The lock-in wind speed regions and vibration amplitudes were investigated and the test results are shown in Fig. 6.

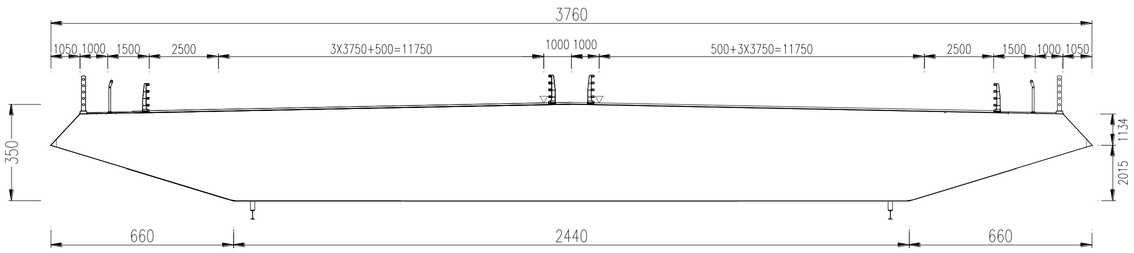


Fig. 4 Cross-section of main girder (unit: cm)

Tab. 2 Main test parameters of the section model

Parameter	Unit	Actual bridge	Section model
Equivalent mass	kg/m	33000	13.2
Equivalent moment of inertia	kg·m2/m	8414000	1.33
Vertical vibration frequency	Hz	0.2922	3.08
Torsional vibration frequency	Hz	0.5607	5.89
Vertical damping ratio	%	---	0.4
Torsional damping ratio	%	---	0.4

As shown in Fig. 6, no vortex-induced vibration occurs under 0º and -3º wind attack angle while there are two significant lock-in wind velocity regions under 3º wind attack angle. The maximum amplitudes are 764mm and 1322mm, under the wind speed of 10.9m/s and 22.7m/s respectively. The vortex-induced vibration amplitudes are beyond the specification (JTG/T D 60-01, 2004), therefor aerodynamic suppression measures are necessary for structure safety and normal operation of the bridge.

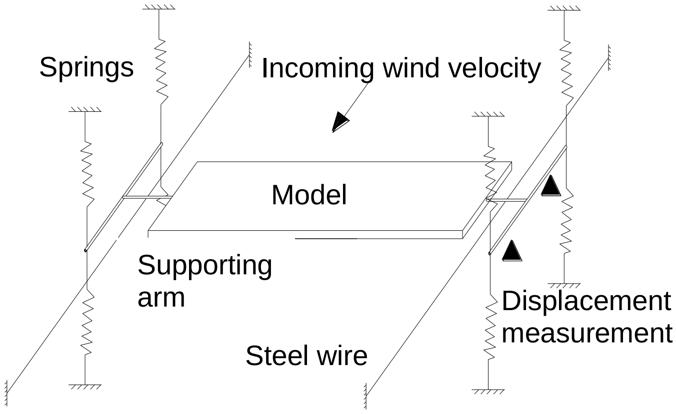


Fig. 5 Elastically-mounted section model

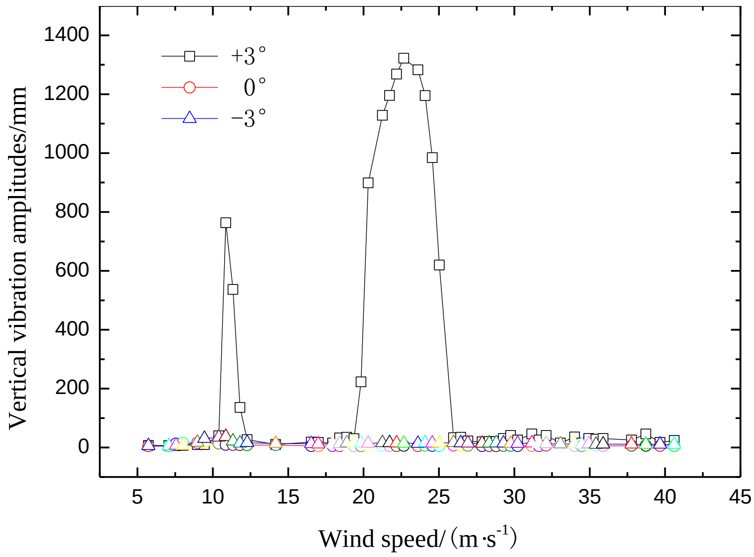


Fig. 6 Vertical responses of vortex-induced vibration

4. CFD ANALYSIS

The development of computer technology and CFD method opened a new way for wind engineering research along with wind tunnel test, which is numerical wind tunnel (Defraeye et al. 2010). By analyzing the fluid characteristics and rules around the girder section through CFD method, the study on vortex-induced vibration suppression measures could be more targeted and efficient.

Transient analysis of two-dimension flow field around the girder section was carried out using CFD software Fluent. The computational domain, 1200m (width) × 400m (height), was divided into 168024 meshes (Fig. 7). SST k-ω model (Menter et al. 1994) was used to serve as a turbulent flow model and the computational time step was set as 0.01s. The pathline pattern around girder section under 3º wind attack angle was obtained by extracting computed results of the velocity field at different time (Fig. 8).

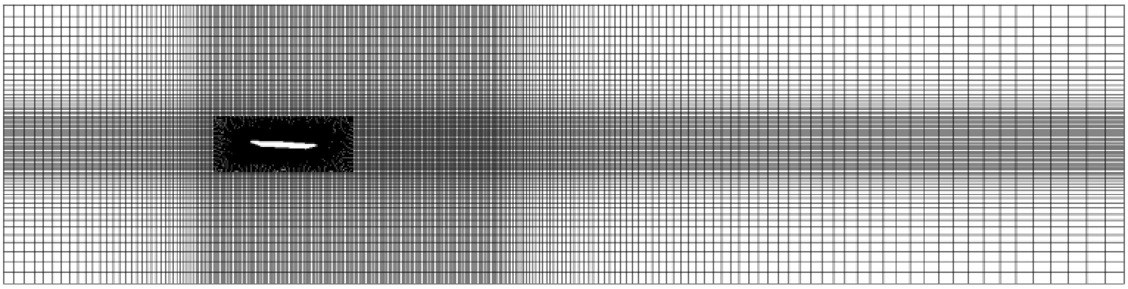
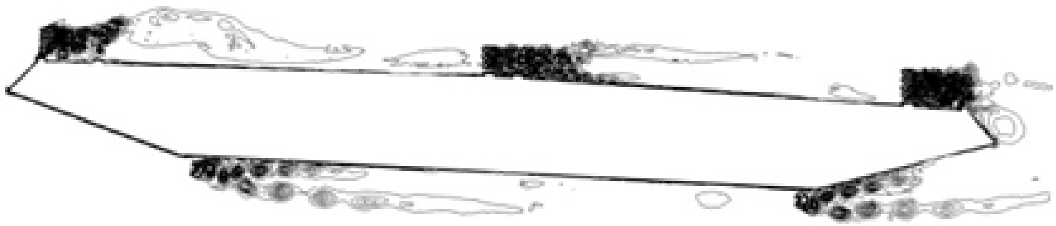


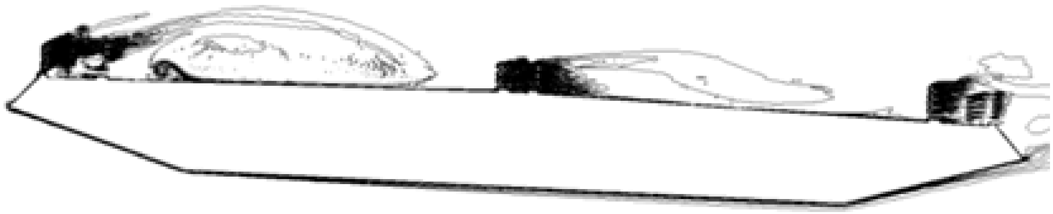
Fig. 7 Mesh of computational domain

Fig.8 Pathline pattern around girder section

Fig. 8 shows a vortex forms behind the upwind railing when the oncoming fluid attacks the girder section at an angle of 3º, and the vortex results in a negative pressure zone on the deck which mostly affects the unsteady aerodynamics of main girder. Moreover, a number of smaller vortexes occur in the downwind of the maintenance rail. The formation and shedding of vortexes repeat periodically near the bottom flange of main girder, which would produce vortex-induced force on the bottom flange and further cause vortex-induced vibration. In order to get more certainty about the influence of the maintenance rails, the girder section without maintenance rail was modeled and analyzed with the same calculation parameters. The contours of vorticity magnitude around the girder section, with and without maintenance rails, were both extracted (Fig. 9).



(b) With maintenance rails



(b) Without maintenance rail

Fig. 9 Contours of vorticity magnitude around girder section (3º wind attack angle)

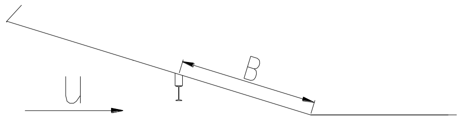
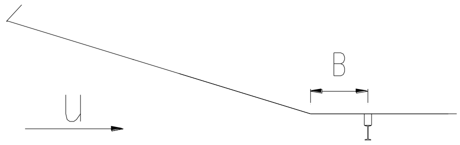
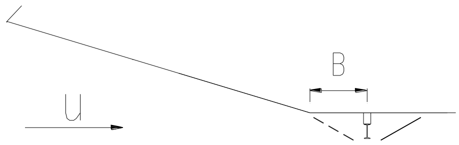
Comparing the calculation results shown in Fig. 9 (a) and (b), the periodic vortexes near the bottom flange disappear completely while the maintenance rails were removed. The results of CFD analysis indicate the maintenance rails are the key factor of vortex forming, thus the research of vortex-induced vibration suppression measures should center around the maintenance rails.

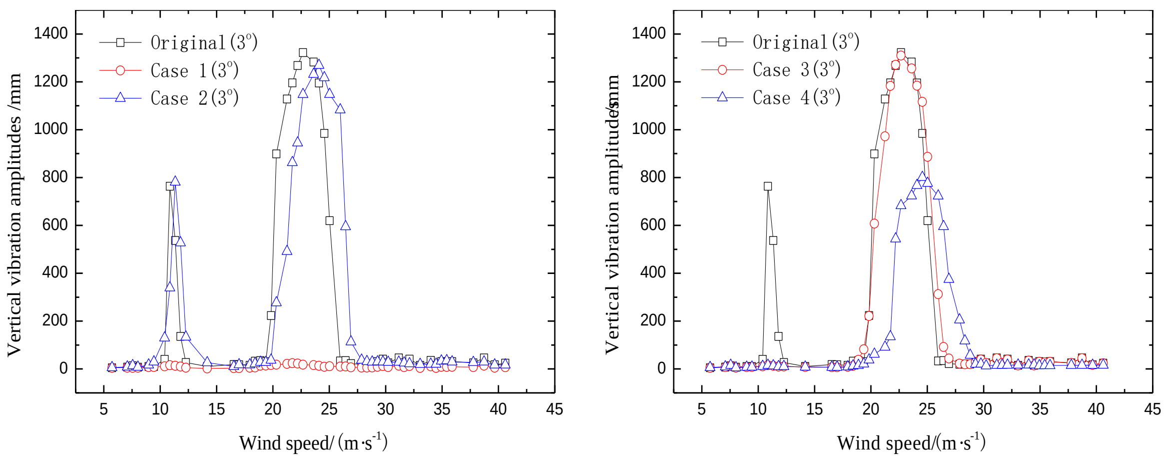
5. TESTS OF SUPPRESSION MEASURES

According to the results of CFD analysis, a series of suppression measures related to the maintenance rails were designed and tested through wind tunnel tests. The mitigation measures of vortex-induced vibration including changing position of the rails and setting guide vanes beside the rails are marked in Tab. 3.

In order to investigate the influence of maintenance rail position, four cases including removing the maintenance rails (case 1), moving the maintenance rails to the girder web (case 2) and changing the distance between the rail and flange edge (case 3~4) were designed and tested by means of section model wind tunnel tests. The vortex-induced vibration amplitudes according to different maintenance rail positions are shown in Fig. 10 (a) and (b).

Tab. 3 Mitigation measures of vortex-induced vibration

	Case 1: maintenance rails removed Case 2: maintenance rails on girder web, B=3.00m
	Change the distance between the rail and flange edge Original: B=0.70m Case 3: B=1.25m Case 4: B=3.00m
	Set guide vanes beside the maintenance rails Case 5: outside guide vane (dotted line), B=1.25m； Case 6: inside guide vane (solid line), B=1.25m； Case 7: outside guide vane (dotted line), B=3.00m； Case 8: inside guide vane (solid line), B=3.00m；



(a) (b)

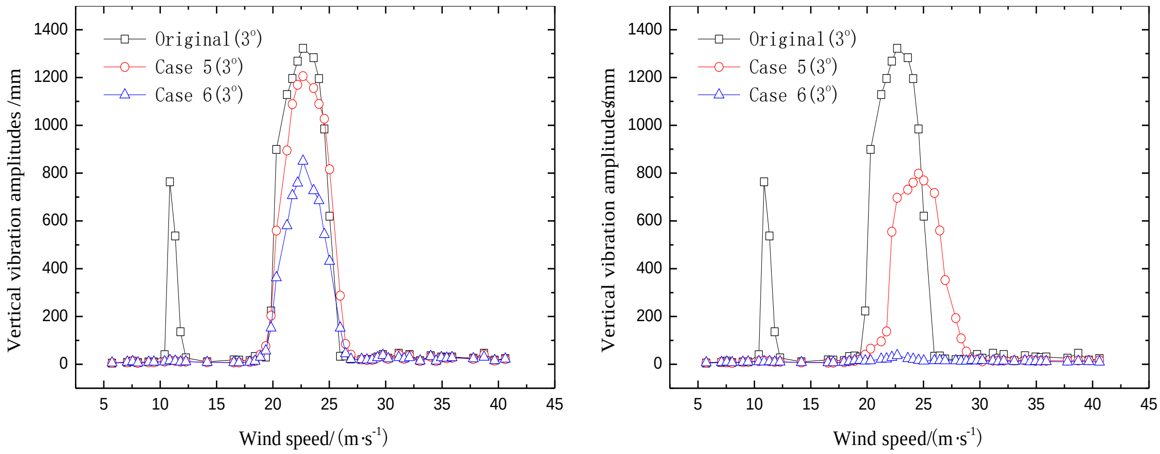
Fig. 10 Responses of VIV for different maintenance rail positions

As shown in Fig. 10(a), the vortex-induced vibration phenomenon almost disappeared after removing the maintenance rails (case 1). It also indicates that moving the maintenance rails from the bottom flange to the web of girder (case 2) just slightly influences the lock-in wind velocity regions and vibration amplitudes.

Fig. 10(b) shows that changing the location of the maintenance rail to 1.25m from the edge of the bottom flange (case 3) can suppress the vortex-induced vibration at the first wind speed lock-in region but can hardly reduce the amplitude of the second vortex-induced vibration region. Furthermore, increasing the distance between the maintenance rail and the bottom flange edge to 3.0m (case 4), the maximum vertical amplitude decreases from 1322mm to less than 800mm.

Changing the position of maintenance rails can reduce the vortex-induced vibration in a certain extent, but the amplitude still exceeds the specification (JTG/T D 60-01, 2004).

Learning from the research results both abroad and at home, four optimization measures of setting guide vane beside the maintenance rail were test in wind tunnel, width of the guide vane ~1.0m, angle between the guide vane and the bottom flange ~30º (as marked in Tab. 3). The results of the vibration responses are illustrated in Fig. 11 (a) and (b).



（a） （b）

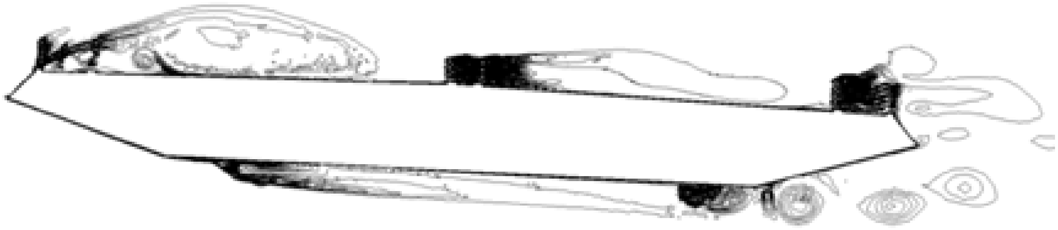
Fig. 11 Responses of VIV for different guide vane positions

By comparing the results of case 3 in Fig.10 (b) and case 5 in Fig.11 (a), it is seen that setting guide vane outside the maintenance rail have little effect on the vortex-induced vibration. The same conclusion could be drawn from the comparison between case 4 and case 7. Otherwise, the guide vane set inside the maintenance rail could significantly reduce the vertical vibration amplitude, as seen in case 6 and case 8. In particular, while the maintenance rail is 3.0m from the bottom flange edge and the guide vane is set inside the rail (case 8), the vortex-induced vibration can be effectively mitigated.

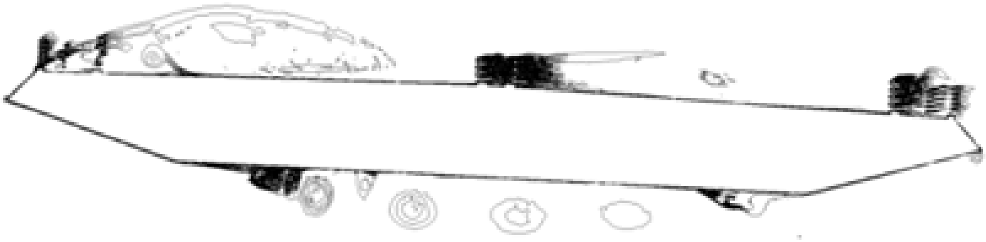
6. MECHANISM OF VIBRATION SUPPRESSION

Through comparing and analyzing the results of wind tunnel tests, the guide vane set inside the maintenance rail could suppress the vibration apparently while the outside guide vane rarely works. To investigate the vibration control mechanism of the guide vane, the cross- section of case 7 and case 8 were both analyzed in two-dimension flow field by Fluent. The contours of vorticity magnitude with guide vanes set outside or inside maintenance rails were shown in Fig. 12 (a) and Fig. 12 (b) respectively, wind attack angle ~3º.

A remarkable difference between Fig. 12 (a) and Fig. 12 (b) is shown above, the different positions of maintenance rails lead to totally dissimilar form of vortex. In case 7, with the guide vanes set outside maintenance rails (Fig. 12 (a)), the flow separated and reattached after flowing through the upwind maintenance rail and also a number of small vortexes formed near the intersection of the rail and the bottom flange. In the leeward side, a series of vortexes form and shed periodically behind the maintenance rail when the reattached flow passing through the leeward maintenance rail. The vortex induced aerodynamic force produced by the alternate vortexes would lead to vortex-induced vibration.



(a) Guide vanes set outside maintenance rails



(b) Guide vanes set inside maintenance rails

Fig. 9 Contours of vorticity magnitude around the girder (3º wind attack angle)

When the guide vanes were set inside maintenance rails (case 8, Fig. 9(b)), some vortexes also occurred behind the upwind rail. However, due to the existence of inside guide vanes, the vortexes that have formed were lead away from the bottom flange of girder and no vortex was found behind the leeward maintenance rail. The analysis results turn out that inside guide vane could change the law of vortex generation and shedding.

For purpose of a more intuitive comparison between the inside and outside guide vanes, the time-history of lift coefficients of the girder section under case 7 and case 8 were obtained through numerical simulation using Fluent. The calculated result is shown in Fig. 10.

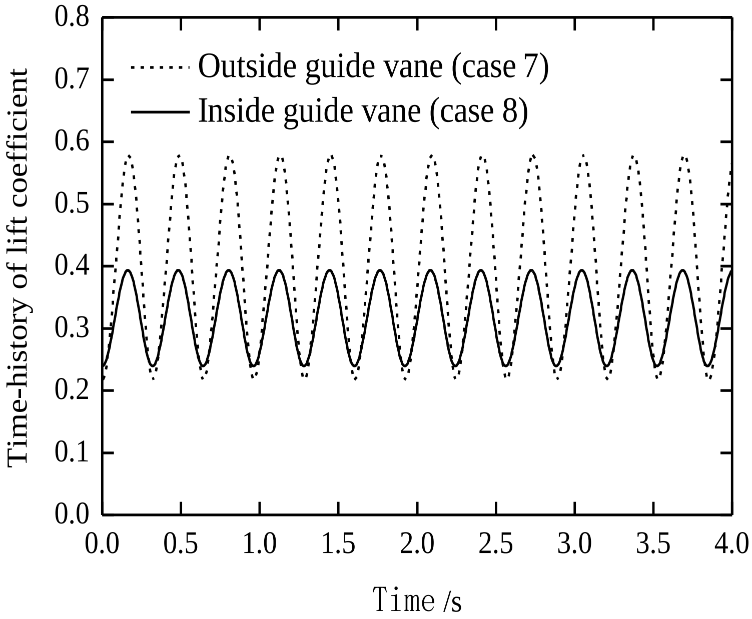


Fig. 10 Time-history of lift coefficients of the girder section

As the above result shows, when the guide vanes move from the outside to the inside of the maintenance rails, the root mean square value of lift coefficient decreased significantly. Without considering the aerodynamic caused by motion of the main girder, the vertical vortex-induced vibration amplitude is positively correlated with the lift act on the girder. Setting guide vanes inside the maintenance rails generated a smaller lift than the outside guide vanes, and as a consequence it had a better effect on vibration suppression.

Last, through a comprehensive comparison of the numerical simulation and wind tunnel test results, in the regard of both different maintenance rail positions and guide vane positions, the analysis results from numerical calculation through CFD method are in good agreement with the vortex-induced vibration responses during the wind tunnel test. It indicates that combining CFD method and wind tunnel test on the research of vortex-induced vibration suppression has high accuracy and practicality.

7. CONCLUSIONS

The section model wind tunnel test and CFD numerical simulation were taken to investigate the vortex-induced vibration suppression measures of streamlined box girder. By analyzing the results from the numerical calculation and wind tunnel test, it can be deduced that the maintenance rail is liable to induce or intensify vortex-induced vibration of streamlined box girder. Changing the position of maintenance rails can reduce the vortex-induced vibration in a certain extent. The guide vane set inside maintenance rail could suppress vortex-induced vibration effectively while the outside guide vane has little effect. The calculated results from CFD method are in good agreement with the wind tunnel test results, indicating CFD method has high accuracy and practicality on the research of vortex-induced vibration suppression of streamlined box girder.

ACKNOWLEDGEMENTS

The support for this work was provided in part by National Program on Key Basic Research Project (Grant No. 2013CB036300) and National Natural Science Foundation of China (Grant No. 51378442 and No.51408505).

REFERENCES

JTG/T D 60-01. (2004), “Wind-resistent Design Specification for Highway Bridges”, Beijing: China Communications Press. (in Chinese).

Larsen, A.， Savage, M., Lafrenière, A.， et al. (2008), “Investigation of vortex response of a twin box bridge section at high and low Reynolds numbers”, *Journal of Wind Engineering and Industrial Aerodynamics*, **96**(6), 934-944.

Li, Y. L., Hou, G. Y., Xiang, H. Y., Zhou, P., Liao, H. L. (2011), “Optimization of the vortex induced vibration for steel box girder of long span suspension bridges by wind tunnel test”, *Acta Aerodynamica Sinica*, **29**(6), 702-708.

Liu, J. X. (1995), “Vortex induced vibration and its control in responses of bridge to wind”, *China Journal of Highway and Transport*, **8**(2), 74-79.

Menter, F. R. (1994), “Two-equation eddy-viscosity turbulence models for engineering applications”, *AIAA Journal*, 1994, **32**(8), 1598-1605.

Sarwar, M. W.， Ishihara, T. (2010), “Numerical study on suppression of vortex-induced vibrations of box girder bridge section by aerodynamic countermeasures”, *Journal of Wind Engineering and Industrial Aerodynamics,* **98**(12), 701-711.

SUN, Y. G., Liao, H. L., Li, M. S. (2012), “Mitigation measures of vortex-induced vibration of suspension bridge based on section model test”, *Journal of Southwest Jiaotong University*, **47**(2), 218-223.

Thijs, D., Bert, B., Erwin, K., et al. (2010), “Aerodynamic study of different cyclist positions: CFD analysis and full-scale wind-tunnel tests”, *Journal of Biomechanics*, **43**(7), 1262-1268.

Xian, R., Liao, H. L., Li, M. S. (2008), “Calculation of spanwise vortex-induced vibration responses of long-span bridge girder”, *Journal of Southwest Jiaotong University*, **43**(6), 740-746.

Xian, R., Liao, H. L., Li, M. S. (2009), “Analysis of vortex induced vibration of large-scale section model of girder in wind tunnel”, *Journal of Experiments in Fluid Mechanics*, **23**(4), 15-20.

Xu, H. T., Liao, H. L., Li, M. S., He, Y. (2009), “Wind tunnel test study of sectional model of Baling River Bridge”, *World Bridges*, **30**(4), 30-33.

Zan, S. J. (1987),“The effect of mass wind angle and erection technique on the aeroelastic behaviour of a cable-stayed bridge model”, *NAE-AN-46*, NRCC.

Zhu, S. Y., Li, Y. L., Shen, J. X., Zhang, Y. (2015), “Optimization of vortex-induced vibration of flat steel box girders at large attack angle by wind tunnel test”, *China*

Civil Engineering Journal，**48**(2), 79-86.