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On Vortex-Induced Vibration Mechanisms of a Flat-Closed-Box Girder via Analysis of Distributed Pressures

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Abstract

This paper investigates the vertical vortex-induced vibration (VIV) of a flat-closed-box girder using numerical simulation method. The accuracy of simulation results are verified at first by comparing the displacement responses and vortex-induced force (VIF) of vertical VIV with those obtained in a previous wind tunnel test of large-scale sectional model. An attempt is made to relate the distributed vortex-induced pressures (VIPs) to the vortex structures, and then the evolution law and distribution of energy for aerodynamic damping pressures are discussed. The results show that the linear aerodynamic negative damping and nonlinear aerodynamic positive damping are key factors of the rapid development of VIV and the self-limiting phenomenon separately, and those areas that contribute aerodynamic damping are found.

Introduction

With the increase of bridge span length, the stiffness and stability of modern long-span bridges decrease obviously. Thus, the long-span bridges are often subjected to VIV, such as the Storebelt Bridge and the Wye Bridge. According to the observation of numerous bridges, it can be concluded that VIV is a limited amplitude vibration without disastrous consequences, but it can cause discomfort to drivers and even structural fatigue to bridges. Therefore, VIV has been taken seriously and some classical research about VIV has been made, such as Scanlan [1], Simiu Ehsan and Scanlan [2], Larsen [3] and Scanlan [4]. At the 21th century, Computational Fluid Dynamics (CFD) method was extensively used in research fields of VIV of bridges for its advantage of visualization and convenience. Sun attested that aerodynamic coefficients can be acquired though CFD with k-ω turbulence model [5]. Hallak discussed the aerodynamic behaviors of a bridge deck with tall vehicle though 2D numerical simulation [6]. However, the results of these numerical simulations either doesn't agree well with the test or field-measurement results, or are not validated with proper test or measurement results.

Although there have been a great deal of researches on VIV of bridges, most of them have focused on the responses of VIV whilst only a few of researches have involved in the nonlinear mechanisms of the VIV and the VIF. Diana indicated that the VIF on a multi-box deck has nonlinear characteristics significantly [7]. Sarwar and Ishihara discussed the vibration reduction mechanism of VIV of a bridge deck with some countermeasures [8]. Zhu revealed from a macro perspective of VIF that the linear aerodynamic negative damping provided by the linear term of response velocity in the vertical VIF on either a flat closed-box deck or a centrally-slotted box deck is the major source of power driving the development of the vertical VIV while the nonlinear aerodynamic positive damping provided by the cubic term of response velocity in the vertical VIF is the inherent key factor leading to the self-limited amplitude phenomenon of the vertical VIV [9,10].

However, the above-mentioned research has been carried out very rarely from a meso-perspective of the VIP distribution. Namely, it has been not clear in which zones of the deck surface the VIPs provide the linear aerodynamic negative damping or the nonlinear aerodynamic positive damping, and this is just the aim of this study. It should be noted that investigations on the contributions of VIPs in various zones of the deck surface to the VIF and the VIV response are significant and are helpful to carry out a target-oriented invention of proper or effective aerodynamic countermeasures. However, relevant research is still very limited.

Numerical simulation and validation

The numerical simulation method and simulation results were introduced in previous research, and also the simulation results were verified by compared with the results of wind tunnel tests in that study. More detail information about this part is introduced by Chen [11,12].

Mechanics explanation of stable stage of VIV

Determination of VIP of each point

As introduced in [9], the interaction between the vibrating model and surrounding air will cause the non-wind-induced additional inertia force and damping force in wind tunnel tests. This interaction also exists in numerical simulation actually, and in a similar way, the VIPs of 301 points in numerical simulation also can be extracted from the pressures. More detail information about this process is introduced by Zhu [9].

Determination of vortex structures

Hunt proposed to use the Q-criterion to describe the vortex structures [13]. For two dimensional incompressible flows, the second invariant Q can be written as

$$Q = \frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial v}{\partial x}\frac{\partial u}{\partial y} \tag{1}$$

The relation between the distributed VIPs and the vortex structures at the stable stage

In this study, some efforts were made to search the relation between the pressures and the flow fields, as shown in Figure 1. For each moment, two subfigures are listed: the left subfigures show the distributed VIPs during a cycle of stable stage of VIV, whilst the right subfigures illustrate the vortex structures at corresponding moment. And the contour lines located at the interior of the girder are positive pressures, while the contour lines located at the outside of the girder are negative pressures in Figure 1. It needs to be emphasized that there may be some mismatches in Figure 1, because the VIPs are dynamic pressures, but the flow fields include both the dynamic flow fields and the mean flow fields. Regardless of the pressures caused by the mean flow fields, such as the mean negative surface pressures caused by the swirl, and then the following descriptions and conclusions are made.

The cycle begins at the rest position (y=0), as shown in Figure 1(a). It can be seen that several small leading edge vortices are formed on the upper surface. Meanwhile, there is a huge vortex locates at the middle and downstream roof, and negative peak VIPs are attained by this vortex formation. On the lower surface of the girder, the flow field is relative stable, and because the wind attack angle is +5°, the VIPs are positive. At the downstream web, there is obvious vortex shedding phenomenon; negative VIPs are caused by this phenomenon.

As shown in Figure 1(b), the flat-closed-box girder reaches the positive displacement peak. It can be seen that the huge vortex moves downstream continually, and the negative VIPs attained by this vortex decrease slightly. At the upstream roof, another huge vortex structure is gradually integrated by several small vortices; due to gradual growth of this vortex structure, most of the VIPs located at the upstream roof are positive, especially at the center of the vortex structure. Around the downstream wind fairing, part of the vortex sheds away from the girder, and part of the vortex moves to the underside of downstream web; as the size of vortex and the vortex shedding, the VIPs at the downstream web decrease slightly.

As shown in Figure 1(c), at the downstream roof, main part of the huge vortex sheds from the girder, only a small part remains at the tail of roof. Thus, the negative VIPs caused by this vortex decrease and some of VIPs change to positive. The huge vortex structure located at the upstream roof increases slowly and almost remains static and the corresponding positive VIPs decrease continually. Furthermore, because of the downward movement of the girder, the vortex located at the underside of downstream web moves to the downstream wind fairing and then sheds.

Then the flat-closed-box girder reaches the negative displacement peak, as shown in Figure 1(d).The huge vortex moves downstream, but because of the existence of the central barriers, main part of the vortex structure remains, only small part moves to the downstream roof. As the movement of vortex, the values of VIPs on the upstream roof decrease and the values of VIPs on the downstream roof decrease on the roof of the girder. And a vortex forms at the underside of the downstream web again.

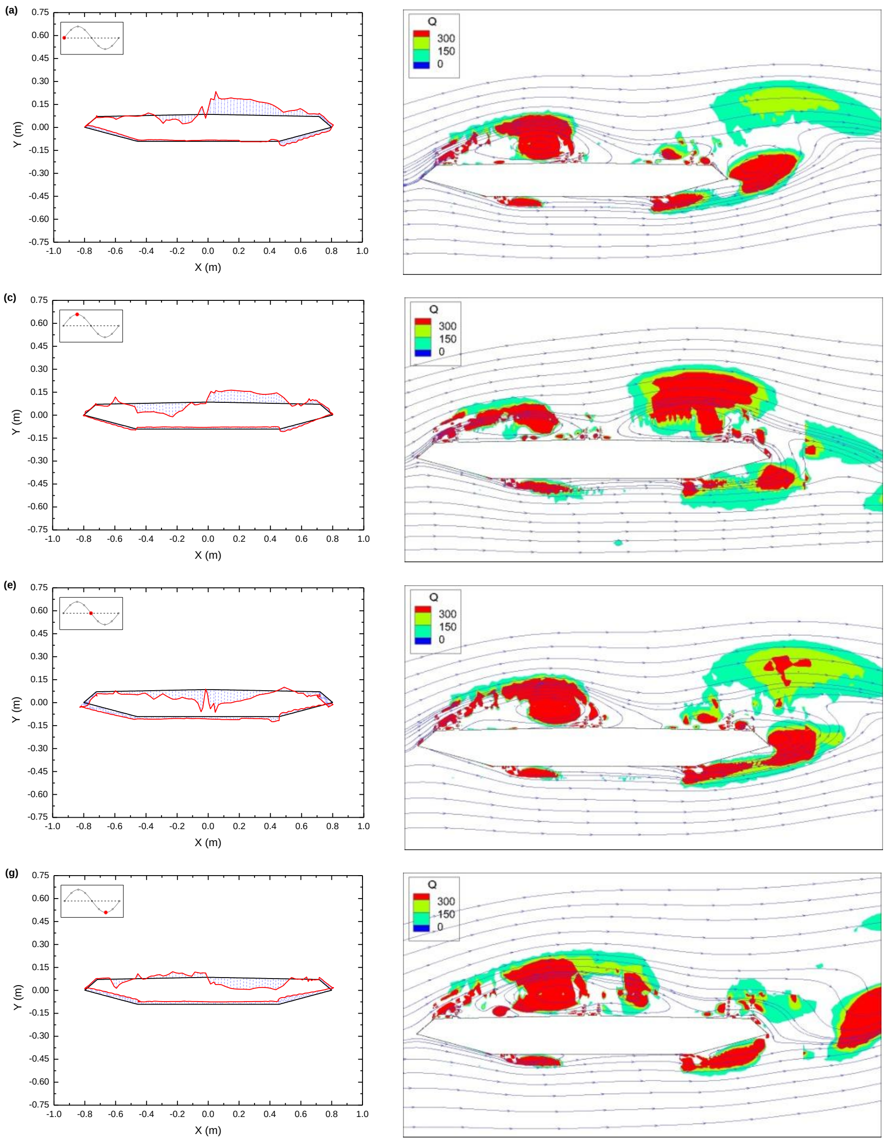

Figure 1. Distributed VIPs and vortex structures during one cycle of stable stage of VIV

Mechanics explanation of development process of VIV

Determination of aerodynamic damping pressures

According to [9], for this type of girder, the VIF can be expressed by the improved mathematical model

$$f_{VI} = \frac{1}{2}\rho U^2 (2D)\left[Y_1\left(1-\varepsilon\frac{\dot{y}^2}{U^2}\right)\frac{\dot{y}}{U} + Y_2\frac{y}{D} + Y_3\frac{\dot{y}}{U}\frac{y}{D} + \frac{1}{2}C_L \sin\left(K_{VS}\frac{U}{D}t+\Phi\right)\right] \quad (2)$$

where ρ is the air density; U is the wind speed; D is the height of the girder; K_{VS} is the circular frequency of vortex shedding; Φ is the phase difference between the vortex shedding and displacement response. It can be seen that the VIF is decomposed by several components. Similarly, the VIPs can be decomposed in the same way, and the summation of each component of VIPs must equal to each component of total VIF. As reported by Zhu [9,10], the linear aerodynamic negative damping force provides energy for VIV, and the nonlinear aerodynamic positive damping force dissipates energy during VIV. Therefore, only the linear aerodynamic negative damping pressures ($Y_1 \rho U D \dot{y}$) and the nonlinear aerodynamic positive damping pressures ($-\varepsilon Y_1 \rho D \frac{\dot{y}^3}{U}$) would be discussed in further analysis.

The evolution law and distribution of energy for aerodynamic damping pressures

As is known to all, for the contribution of force to the VIV, the discussion about the amplitude of the force is not appropriate, because the phase between force and displacement may be different. And the traditional approach is to discuss the work of force to this girder. It means that does positive work provides energy for the movement of structure, and does negative work dissipates energy and obstructs the movement of structure. In this section, in which zones of the deck surface the VIPs provide the LADPs or NADPs was found, whilst the quantities of energy provided by linear aerodynamic negative damping pressures (LADPs) or dissipated by nonlinear aerodynamic positive damping pressures (NADPs) were also determined.

As shown in Figure 2, it is the vertical displacement response of VIV. In order to explore the energy evolution law, the process of VIV is divided into three stages: the first stage is the stage of rapid development and contains fifteen cycles; the second stage is the stage of gradual convergence and also contains ten cycles; the third stage is the stable vibration period, and five cycles among the last stage are selected as the object to analyze.

The analysis results show that only the absolute value of linear aerodynamic damping work (LADW) increases, but the outline of LADW keeps same at each stage. So does nonlinear aerodynamic damping work (NADW). The reason is as follows. According to Equation (2), all the LADPs and the NADPs are merely related to velocity of each point which equals to the velocity of the girder. It means that there is no phase difference for all the aerodynamic damping pressures. In the same way, all the aerodynamic damping work fluctuates synchronously. Therefore, the contours of aerodynamic damping work keep same, except the absolute values increase. Thus, Figure 3 only shows the average energy distribution in one cycle of LADPs, NADPs at the fourth stage for as a schematic. In Figure 3, the contour lines located at the outside of the girder mean that these pressures do positive work, and the contour lines located at the interior of the girder indicate that these pressures do negative work. Moreover, it needs to be stressed that these contour lines are magnified in different multiple for convenience of observation.

One can also find from Figure 3 that at the middle and downstream roof, the contour of LADW is significant. It means that the LADPs contribute a lot of energy to VIV at the middle and downstream roof. Moreover, the energy contributed by LADPs at the upper of upstream web and the floor also cannot be ignored. For the NADPs, they significantly dissipate energy at the floor and the middle of upper surface. It is because of the existence of central barriers, the force distribution is disorder at the middle of upper surface, thus, the situation of doing work of aerodynamic damping pressures here is complex.

The distributions of energy for each type of pressure were discussed above, and for a quantitative analysis of evolution law of energy, the quantities of energy for each type of pressure at every stage were determined as shown in Table 1. It can be found that besides VIPs, there is also a structural damping force exerted on the flat-closed-box girder. Obviously, the LADPs and vortex-shedding pressures provide energy to VIV, but the NADPs and the structural damping force dissipate energy all the time. Also, Table 1 demonstrates the significance of the vortex-shedding pressures at the first stage.

At the first stage, the VIV develops rapidly. As the amplitudes of displacement and velocity are small, the NADPs which are proportional to the cube of velocity are very small, so very little energy is dissipated by the NADPs. Also, the product of structural damping and velocity is small, thus, the energy dissipated by the structural damping force is also little. Therefore, it can be found that this girder absorbs a lot of energy to promote the rapid development of VIV, especially at the second stage.

The average amplitude of displacement at the third stage is much higher than that at the second stage, also the average amplitude of velocity increases significantly. As illustrated in Table 1, the absolute values of energy for each type of pressure increase rapidly, especially the energy dissipated by NADPs, which cannot be ignored in this period. Although the growth rate of the dissipated energy is larger than that of the absorbed energy, the quantity of the dissipated energy is smaller than that of the absorbed energy. Thus, at the third stage, this girder also absorbs energy to supply the VIV, but the total absorbed energy decreases obviously compared with the previous stages.

Both the average amplitude of displacement and velocity increase slightly compared with the third stage, so the absolute values of energy for each type of pressure also increase. Similar to the third stage, the growth rate of the dissipated energy is also larger than that of the absorbed energy, and the total absorbed energy continue decreases. As shown in Table 1, the total absorbed energy is almost zero, it means that the energy provided by LADPs equals to the energy dissipated by NADPs and structural damping force, so that the VIV is in balance.

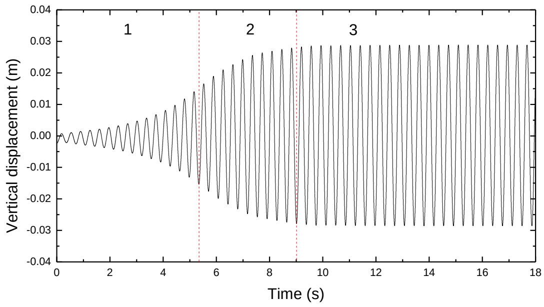

Figure 2. Vertical displacement response.

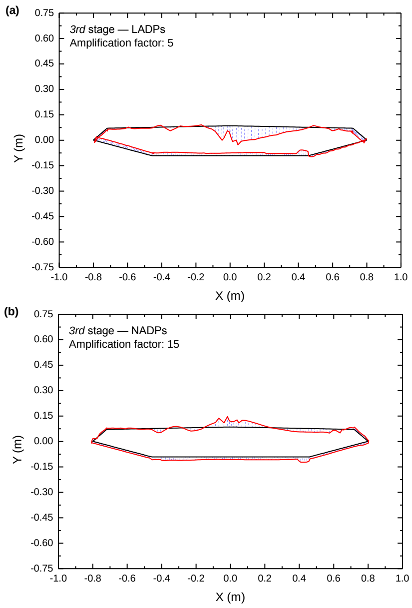

Figure 3. Energy distribution at the stable stage.

Type of pressures	1st stage	2nd stage	3rd stage
LADPs	0.086	0.521	0.855
NADPs	-0.002	-0.105	-0.198
Vortex-shedding pressures	0.004	0.004	0.003
VIPs	0.088	0.420	0.661
Structural damping force	-0.019	-0.407	-0.660
Total	0.069	0.013	0.000

Table 1. Quantities of energy for each type of pressure at every stage (J).

Conclusions

Studies on the vortex-induced vibration of a flat-closed-box girder based on distributed pressures were carried out through numerical simulation in this study. The major works and some conclusions are drawn below.

- It can be found that the direction of the VIPs at the rest of the girder is synchronized with the direction of motion of the girder, except the upstream roof. Moreover, the area with large pressure value contains the middle and downstream roof and the underside of upstream web and the floor.
- The linear aerodynamic negative damping pressures contribute a lot of energy to VIV at the middle and downstream roof. At the floor and the middle of upper surface, the nonlinear aerodynamic positive damping pressures dissipate energy significantly.
- At the rapid development period of VIV, the LADPs are the key factor of the rapid development of VIV. And the NADPs play key roles for the self-limiting phenomenon. At the stable stage of VIV, the absorbed energy and the dissipated energy reach equilibrium, which leads to the stable VIV continues.

Furthermore, it needs to be emphasized that the author has done some early research on VIV [12], since the symbol of the nonlinear aerodynamic damping force was incorrectly written at that time, the third conclusion of this study is opposite with that of references [12]. The author hereby declares and corrects.

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