Numerical studies on suppression of vortex-induced vibrations of a twin box girder by central grids

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ABSTRACT

A numerical study with Delayed Detached Eddy Simulation (DDES) is carried out to investigate the aerodynamic mechanism on the suppression of vortex induced vibrations (VIV) of twin box girders by central grids, which can mitigate the VIV by section model wind tunnel tests. The mean aerodynamic force coefficients with different attack angles were compared with the experimental results to confirm the numerical results. Then the flow structure around the deck and the aerodynamic forces on the deck are analyzed in order to enhance the understanding of appearance of VIV and the mechanism of suppression by central grids. The results show that shear layers are separated from the upper railings and lower overhaul track of the upstream girder, and induces the large scale vortices formed in the gap, which would cause periodical lift force with large amplitude on the downstream girder and result in appearance of VIV. However, the VIV are obviously suppressed by the central grids due that the vortices in central vent becomes weaker and cause a smaller fluctuating lift forces on the deck. In addition, the mean total lift on the deck is mainly contributed by the upstream girder, while the fluctuating lift is mainly contributing by the downstream girder.

Keywords: twin box girders; vortex-induced vibrations, central grids; CFD simulation

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1. Introduction

As for the safety of long span bridge against wind loads, it is very important and essential to investigate the wind-induced oscillations, such as flutter, vortex-induced vibrations. With the increase in span length, twin-separated steel box girder section will be extensively used in long-span bridges to improve aerodynamic stability (Ge and Xiang 2008), for example, the Xihoumen suspension bridge (main span: 1650m, China), the Stonecutters cable-stayed bridge (main span: 1018m, Hongkong), the Gwangyang suspension bridge (main span: 1545m, Korea). Recently, a new twin box girder suspension bridge named Lingdingyang Bridge with main span of 1660m is planning to construct in south of China as shown in Fig.1 and 2.

Compared to the higher critical flutter speed of this kind of two box girders (Ogawa, Shimodoi et al. 2002; Matsumoto, Shijo et al. 2004; Hui, Ding et al. 2006; Yang and Ge 2009; Kwok, Qin et al. 2012; Trein, Shirato et al. 2015), the VIV may happen for twin box girder due to the complicated flow around the box and effects of gap, as well as the interference between the two girders. Thus a lot attention were paid to the VIV of long span bridge with two box girders. Chen, Niu et al. (2007) studied the wind-induced vortex shedding of two parallel box-girder bridges by wind tunnel tests. It shows that the aerodynamic interference cannot be ignored and it will affect the vortex-induced vibration of both decks. Larsen, Savage et al. (2008) found the obvious vortex-induced vibration of Stonecutters bridge with a twin box girder section, and investigated experimentally the suppression of guide vanes. Li, Laima et al. (2011) investigated the vortex-induced vibration of a twin steel box girder suspension bridge with a main span of 1650 m based on field measurements, and mentioned that the vortex-induced vibration more likely occurs in a low wind speed range of 6~10 m/s, with the wind direction nearly perpendicular to the bridge line, and low turbulence intensity. Chen, Li et al. (2014) studied the unsteady vortices and turbulent flow structures around twin-box-girder bridge deck models with different gap ratios by section model tests. Kargarmoakhar, Chowdhury et al. (2015) investigated experimentally the effects of Reynolds number on the aerodynamic characteristics of a twin-deck bridge in the range
of $\text{Re}=1.3\times10^6$--$6.1\times10^6$. They found that a larger separation bubble formed on the bottom surface of the upstream girder accompanied with a narrower wake region with increasing of Re number. Yang, Zhou et al. (2016) carried out a series of wind tunnel tests to investigate the VIV performance and countermeasures for twin-box girder bridges and mentioned that the application of grid plates has positive effects in suppressing the heaving VIV responses.

Meanwhile, with the development of computational fluid dynamic (CFD), more and more researchers investigate the aerodynamic behavior of a bridge deck, as well as the VIV performance by computational approach. Nieto, Kusano et al. (2010) carried out a 2D numerical study to investigate the vortex-shedding response of a twin-box deck cable-stayed bridge and obtained reasonable results. de Miranda, Patruno et al. (2015) performed LES and RANS to simulate the flow around twin box girders with four different gap spaces. Their results showed that LES provides better results than RANS. In addition, Sun, Owen et al. (2008) suggested that the $k-\omega$ performs better than $k-\varepsilon$ for wall flow simulation as the later over-produces the turbulence kinetic energy near the wall changing the flow patterns. Therefore, the DDES with SST $k-\omega$ model was applied to simulate flow around this twin box girders.

Basing on the above observations, there are many researches on the VIV performance of twin box girders and put forward some aerodynamic countermeasures to control the VIV. However, less attention were paid to the mechanism of VIV, as well as the mechanism of aerodynamic countermeasures. Hence, in the present study, the flow around the two box girders are investigated by performing two-dimensional Delayed Detached Eddy Simulations with SST $k-\omega$ model at Reynolds number $\text{Re}=U_\infty D/\nu=2.5\times10^4$ (same as that in wind tunnel tests), where $U_\infty$ is the free stream velocity, $D$ is the thickness of the deck, and $\nu$ is the kinematic viscosity. The numerical method and numerical details applied in this study are first described and verified by presenting the mean aerodynamics coefficients and Strouhal number. Then, we focus on the time-averaged and instantaneous flow structures, pressure distributions and forces on two girders in order to the underlying mechanism of VIV and suppression of central grids. In addition, the components of the total aerodynamic forces were analyzed.

2. Description of the experiment

In this study the wind tunnel tests were used in order to compare the obtained numerical results to experimental data. The experimental study has been conducted in a closed-circuit wind tunnel with a test section of 2.4 m height×2.0m width×16.0m length, where wind velocity range from 1.0m/s to 45m/s. A test set-up, which was specially designed to carry out static and dynamic tests of bridge deck section and mounted on the outside walls of wind tunnel, was used in the wind tunnel testing. The dynamic model (1:70) was suspended by 4 pairs of linear springs and could vibrate vertically and torsionally as shown in Fig. 3. The static model was performed for attack angles from -12° to 12° with step of 1° in order to obtain the aerodynamic coefficients,
and the dynamic deck model was tested for five attack angles 0°, ±3° and ±5° under smooth oncoming flow.

![Sectional Model](image)

**Fig.3 Schematic diagram of model test**

The three components of static wind load are drag force, lift force and pitch moment. Consider a section of bridge deck in a smooth flow, the tri-components of aerodynamic forces per unit span acting on the deformed deck can be written in wind axes as following:

\[
F_D = \frac{1}{2} \rho U^2 C_D(\alpha) D , \\
F_L = \frac{1}{2} \rho U^2 C_L(\alpha) B , \\
F_M = \frac{1}{2} \rho U^2 C_M(\alpha) B^2
\]  

(1)

Where \( F_D, F_L, \) and \( F_M \) drag force, lift force and pitch moment, respectively; \( \rho \) is the air density; \( U \) is the wind velocity; \( C_D(\alpha), C_L(\alpha) \) and \( C_M(\alpha) \) are the coefficients of drag force, lift force, and pitch moment in wind axes, respectively; \( \alpha \) is the effective attack angle of wind. \( B \) is the deck width. Meanwhile, the aerodynamic coefficients of this twin box girders were obtained by static sectional-model wind tunnel tests as shown in Fig. 4.
As in the dynamic sectional model tests of original twin box girders, two bending VIV regions have been observed with corresponding wind speed of 4~5m/s and 5.5-7.5m/s for all studied attack angles as in Fig. 5. Moreover, the maximum amplitudes (RMS) of vertical vibration are 0.34m and 0.69m, respectively, which is much larger than the both requests of Chinese and British Codes. Hence, the central grids on the upper side of the gap with different flux ratios were employed to mitigate the VIV as shown in Fig. 6. Here the flux ratio is defined as \(\text{Flux ratio} = \frac{(n+1) \times b}{L}\), where \(n\) is the amount of central grids, \(b\) and \(L\) are spacing between two grids and gap, respectively. The flux ratios of 0%, 17%, 25%, 33%, 42%, 50%, 67%, 75% and 83% were studied in present study. As shown in Fig. 7, the VIV is obviously suppressed by setting the central grids with all studied attack angles. The effects of central grids were also found in the experimental studies of Yang, Zhou et al. (2016). However, unlike to their results in which the effectiveness of central grids is more obvious with the decrease of flux ratio, we found that the VIV disappeared in the case of flux ratio of 50%.
In order to investigate the aerodynamic mechanism on the suppression of vortex induced vibrations (VIV) of twin box girders by central grids, the flow around the original deck and the deck with central grids were numerically studied for the most unfavorable attack angle of -3°.
3. Numerical setup

3.1 Governing equations

The numerical model for flows around the two tandem circular cylinders is formulated using the Cartesian coordinate system. Eqs. (1) and (2) show the filtered continuity and Navier-Stokes equations.

\[
\frac{\partial \bar{u}_i}{\partial x_i} = 0
\]  

\[
\frac{\partial (\bar{u}_i \bar{u}_j)}{\partial t} + \frac{\partial (\bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}
\]

where \(u_i\) \((i=1, 2, 3)\) are the three velocity components. \(\rho\), \(P\) and \(\nu\) represent the air density, pressure and kinematic viscosity of the flow, respectively. \(\tau_{ij}\) is stress, which is used as subgrid scale stresses in LES model in far from wall, and \(\tau_{ij}\) is expressed in SST \(k-\omega\) model in near wall region judged by a function as followed (Spalart, Jou et al. 1997; Menter, Kuntz et al. 2003):

\[
F_{DES} = \max \left( \frac{L_t}{C_{DES} \Delta_{max}}, 1 \right)
\]

where \(C_{DES} = 0.61\), \(\Delta_{max}\) is the maximum grid spacing, and \(L_t\) is the turbulence length scale in SST \(k-\omega\) model. However, DES limiter can activate the LES mode inside the boundary layer, where the grid is not fine enough to sustain resolved turbulence. Therefore, a new formulation of DES is employed to preserve the RANS mode throughout the boundary layer (Spalart, Deck et al. 2006). This is known as the delayed option or DDES for delayed DES. The function is modified as followed:

\[
F_{DES} = \max \left( \frac{L_t}{C_{DES} \Delta_{max} (1 - F_{SS}), 1} \right)
\]

Where \(F_{SS}\) is equal to 0, \(F_1\) or \(F_2\) which are the blending functions of the SST \(k-\omega\) model.

3.2 Numerical discretization and algorithm

The simulation is performed with the aid of the Fluent© package. The options offered by Fluent© for simulation are carefully selected or set by User Definite Function (UDF) on the following basis.

In the simulation, the velocity and pressure are defined at the center of a control volume, while the volume fluxes are defined at the midpoint of their corresponding cell surfaces. The Momentum Interpolation Method (MIM) is used to avoid oscillating
problems by eliminating the checkerboard pressure and subsequent refinements with non-staggered mesh. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm proposed by Patankar and Spalding (1972) is utilized, in which governing equations are solved sequentially because of their non-linearity and coupling characteristics and the solution loop is carried out iteratively in order to obtain a converged numerical solution. The pressure field is extracted by solving a pressure correction equation obtained by manipulating continuity and momentum equations, while the velocity field is obtained from the momentum equations. In addition, the convergence criterion of the iterative calculation is set to $1 \times 10^{-6}$, which requires about 10 iterations to satisfy.

In order to avoid instability caused by central-differencing schemes and non-physical wiggles, the bounded central differencing scheme is applied to spatial differencing of the convection term, which is a composite Normalized Variable Diagram (NVD, (Leonard 1991)) scheme that consists of a pure central differencing, a blended scheme of the central differencing and the second-order upwind scheme, and the first-order upwind scheme. Meanwhile, a fully implicit second-order time-advancement scheme is chosen for temporal discretization to obtain stable and accurate simulation.

3.3 Grid system and boundary condition

As shown in Fig. 8, the computational domain is 140D in x-direction, 50D in y-direction. The blockage ratio is 2%, which is smaller than the suggestion (6.4%) of Sohankar (2008).

![Fig.8 Computational domain and boundary conditions](image1)

![Fig.9 Close-up view of grid system](image2)
Fig. 9 presents the grid near the deck and central girders. Structured O-type grid systems with the depth of the first grid near the body surface given empirically as $0.1/\text{Re}^{0.5}$ are applied to adequately resolve the flow. For more efficient simulations, the computational domain is spatially resolved such that a dense clustering of grid points is applied near the wall, especially in the wake zone, while a coarser grid is used away from the wall. For the temporal discretization, the non-dimensional time-step $\Delta t' = \Delta t U / D$ ($\Delta t$: the time-step for calculation) is $2.5 \times 10^{-3}$, which maintains the Courant Number less than 1.

The boundary conditions for simulation, illustrated in Fig.8, are as follows:
Body surface: A no-slip condition for $u_i=0$ and a Neumann condition for pseudo-pressure $\phi$ are imposed.
Inlet: The uniform velocity condition, $u=10\text{m/s}$, $v=0$ and $w=0$, and a Neumann condition of pseudo-pressure $\phi$ are imposed at the inlet boundary.
Outflow boundary: A convective boundary condition ($\partial \phi / \partial t + \overrightarrow{\nu} \cdot \partial \phi / \partial x = 0$) is applied for velocity, and Neumann condition for pseudo-pressure.
Upper and lower sides: A symmetric condition is applied to both velocity and pseudo-pressure.

3.4 Numerical validation
In order to validate the present simulation, the aerodynamic coefficients and Strouhal number of original deck are compared with those of experimental studies.
As shown in Fig. 10, the aerodynamic coefficients of original deck with attack angle $0^\circ$ and $\pm 3^\circ$ agree well with experimental data, although the numerical value is a little bit larger due to the two dimensional simulation.

![Fig.10 Comparison of numerical and experimental aerodynamic coefficients](image)

As shown in the table 1, the Strouhal numbers obtained by the present simulation has a difference less than 8% with those of experiment result, which means the numerical results are consistent with experimental results. Hence, the numerical method and the grid system utilized in the present simulation can provide reasonably good simulation results.
Table 1 Comparison of Strouhal numbers

<table>
<thead>
<tr>
<th>Strouhal number</th>
<th>Experimental result</th>
<th>Numerical result</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>vortex-induced region 1</td>
<td>0.081</td>
<td>0.085</td>
<td>4.94%</td>
</tr>
<tr>
<td>vortex-induced region 2</td>
<td>0.121</td>
<td>0.130</td>
<td>7.44%</td>
</tr>
</tbody>
</table>

4. Results and discussion

4.1 Flow structures

Fig.11 shows the contours of instantaneous vorticity for original deck in one period with attack angle of -3°, where the blue and red colors represent clockwise and counterclockwise vortices, respectively. Similar to the flow pattern of two tandem cylinders named co-shedding regime (Alam, Moriya et al. 2003), the alternate vortex shedding occur in the gap as well as in the wake of downstream girder, which means that the binary vortex street appears. Meanwhile, it can be found that the shear layers separated from the upper railings and lower overhaul track of the upstream girder, which induces the large scale vortices formed in the gap. Then the vortices impinge alternately onto the both up and low sides of downstream girder, which means that the upper vortices formed by the shear layers separated from the upper railings, as well as the lower vortices formed by the shear layers separated from the lower overhaul track, would not only affect the upper surface but also the lower surface of downstream girder. Hence, this flow characteristics would induce a larger lift fluctuation and may cause the vortex-induced vibration.

As shown in Fig.12, the binary vortex street appears in the case of the deck with central grids (here it is named as optimized deck, same as followed) in condition of attack angle of -3°. However, it can be observed that the large scale vortices in the gap are obviously suppressed and smashed into small scale vortices after setting central grids. Moreover, the interaction between the upper and lower vortices become weaker. It can be also found that the upper vortices and lower vortices just impinge onto the upper and lower surfaces of downstream girder, respectively. In addition, the width of vortices movement both in the gap and the wake of downstream girder becomes narrower due to the effects of central grids. It indicates that the fluctuating lift on the downstream girder would be suppressed and becomes smaller, which means that the periodical lift force has a small amplitude and the VIV would be controlled.
Fig. 11 Instantaneous vorticities around the original deck in one period ($\omega = \pm 1.5$)

Fig. 12 Instantaneous vorticities around the deck with central grids in one period ($\omega = \pm 1.5$)

Fig. 13 Time-averaged streamline around the original deck with the attack angle of $-3^\circ$
Fig. 14 Time-averaged streamline around the optimized deck with the attack angle of -3°

Fig. 13 and Fig. 14 show the time-averaged streamline around the original deck and the optimized deck, as well as in their gaps, with attack angle of -3°. As for the original and the optimized decks, it can be found that there are two main vortices behind the oblique web of upstream girder (named first vortex) and in the gap (named second vortex), which are formed by the shear layers separated from the upper railings and lower overhaul track of the upstream girder, respectively. Zhou, Yang et al. (2015) also found the similar phenomenon in their numerical simulations. It indicates again that the two VIV lock-in regions are induced by these two main vortices, respectively. As shown in Fig. 13, the flow which passes over the upper side of upstream girder has a significant downward velocity at the central gap and impinge onto the bottom of the downstream girder. This also illustrates that interfere between the upper and lower vortices is strong and the large-scale vortices formed by upstream girder impinges alternately onto the upper and lower surfaces of downstream girder.

However, after setting of central grids in the gap, the second vortex is obviously suppressed and become much smaller as shown in Fig. 14. Meanwhile, the downward flow in the gap is significantly inhibited, which illustrates that the interaction between the upper and lower vortices is obstructed due to the existing of central grids. The change of flow structures around the deck has direct influence to the forces on the deck, especially the fluctuating forces In addition, the vortices in the wake of downstream girder is weaker than that in the wake of upstream girder as for both the cases of original and the optimized decks. It demonstrates that the total mean drag and lift forces on the deck are mainly contributed by the upstream girder, which will be discussed in detail as in the followed section.

4.2 Aerodynamic forces

In order to further explain the aerodynamic mechanism of the central grids to suppress the VIV of two twin box girders, the aerodynamic forces, based on the flow behavior around the deck, are analyzed in this section. Fig. 15 presents the contour of fluctuating pressure around the original and the optimized decks. It shows that the fluctuating pressure distribution of the original deck is more extensive, especially in the central slot and around the downstream girder. Moreover, as for the original deck, the pressure on the bottom surface of downstream girder shows more pulsating. The reason is that the intensity and scope of impingement of the vortices onto the downstream girder is weakened by setting of central grids.
Fig. 16 presents the time-history of total lift and lift on the downstream girder, where the red line represents these lift coefficients of the optimized deck and the black one is for the original deck. It is well known that the factors that determine the vortex-induced vibration are mainly the vortex frequency and the amplitude of the lift fluctuation. As shown in the Fig. 16, the domain frequency of the total lift coefficients, as well as the mean lift coefficients, is almost unchanged with the setting of central grids. However, the total lift fluctuation (RMS value of lift coefficients) on the original deck is 0.113 and decreases obviously to 0.055 of the optimized deck as shown in the table 2. Similarly, the lift fluctuation on the downstream girder is also clearly suppressed and decreases from 0.096 to 0.050. This is due that the vortices which impinging onto the downstream girder are suppressed by the central grids and become weaker as mentioned above. It means that the mechanism of suppress of VIV by central grids is the decrease of fluctuating lift, rather than the change of vortex shedding frequency.

<table>
<thead>
<tr>
<th>Cross section</th>
<th>Mean total lift</th>
<th>Mean lift on downstream girder</th>
<th>RMS of total lift</th>
<th>RMS lift on downstream girder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original deck</td>
<td>-0.255</td>
<td>-0.089</td>
<td>0.113</td>
<td>0.096</td>
</tr>
<tr>
<td>Optimized deck</td>
<td>-0.257</td>
<td>-0.093</td>
<td>0.055</td>
<td>0.050</td>
</tr>
</tbody>
</table>
In addition, we also analyze the components of mean and fluctuating lift forces in order to enhance the understanding of suppress of central grids and the characteristics of aerodynamic forces as shown in Fig. 17. Whether it is the original deck or optimization deck, the contribution of the mean lift on the downstream in total lift is greater than 62%. This is because that the first vortex exists behind the trailing oblique webs of upstream girder. As for the fluctuating lift, the total fluctuating lift is mainly provided by the downstream girder, which is accounting for nearly 80%. This means that the mean total lift is mainly contributed by the upstream girder, while the fluctuating lift is mainly contributed by the downstream girder. This phenomenon is similar as that of staggered cylinders (Sumner 2010; Zhou and Alam 2016). In addition, it should mention that both the mean and fluctuating lifts on central grids are less than 10% as in the total mean and fluctuating lifts, respectively.

5. Conclusions

Delayed Detached Eddy Simulation (DDES) is performed to investigate the flow over two twin box girders at Reynolds number Re=2.5×10^4. The Strouhal number, drag, lift and pitch moment coefficients, as well as the unsteady wake structures are studied in order to enhance understanding of VIV performance and the suppression of central grids. Some conclusions are summarized as follows:

- The severe vertical vortex-induced vibration phenomenon are found as for the original two box girder as a result of large scale vortices in the central vent, which induce obvious lift fluctuation on the downstream girder.
- The VIV are obviously suppressed by the central grids in the gap due that the vortices in central vent becomes weaker, which cause a smaller fluctuating lift forces on the deck.
- The mean total lift is mainly contributed by the upstream girder, while the fluctuating lift is mainly contributing by the downstream girder.
Acknowledgments

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