Flutter stability studies of Great Belt East Bridge and Tacoma Narrows Bridge by CFD numerical simulation

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ABSTRACT: In the paper, by secondary development of commercial computational fluid dynamics software FLUENT, establish two-dimensional bending and torsional fluid-structure interaction numerical model to calculate flutter critical wind speed of Great Belt East Bridge and Tacoma Narrows Bridge. According to time histories of vertical displacements and torsional displacements, we can judge flutter critical wind speed and flutter modality. The numerical results show: when the wind speed is more than 63m/s, Coupled vertical-torsional flutter is found in Great Belt East suspension bridge; When the wind speed is more than 8m/s, Torsional dominated flutter is found in Tacoma Narrows Bridge. Critical wind speed of flutter by numerical simulation is in agreement with wind tunnel test. At the same time, this paper uses numerical wind tunnel technique displays the vortex drift along the beam, reveals the interaction between the main beam and vortex motion is one of the reasons leading to divergent vibration.

KEYWORDS: fluid-structure interaction, divergent vibration, vortices movement, bending-torsional coupled flutter, torsional dominated flutter, critical flutter wind speed

1 INTRODUCTION

Flutter is a complex physical phenomenon. It is basically divided into two categories in term of aerodynamic. There is no flow separation phenomenon in streamlined profile object, such as aircraft wings in small angle of attack. When flutter happen at the situation we call it classical flutter. It is first flutter. Second flutter is related with the flow separation and vortex formation. It is likely to occur in the lifting surface in large angle of attack or no streamlined profile building structures. It is called stall flutter.

Bridge flutter is a divergent self-excited vibration, which can potentially result in catastrophic failure of a structure. It is mainly due to vibration of the structure can absorb the energy in the flow air and the energy is greater than energy dissipation of the structural damping in the vibration. There are two types of flutter phenomena in bridge structure: One is bending-torsional coupled flutter another is separated flow flutter. Bending and torsion coupled flutter is generally occurs in the streamlined beam. The majority of bridge deck is non-streamlined. Flow separation phenomenon occur at the corners of the deck where vortex shedding is generated, then single degree of freedom of torsional flutter is likely to occur. It is separated flow flutter.

In the paper, by secondary development of commercial computational fluid dynamics software FLUENT, establish two-dimensional bending and torsional fluid-structure interaction numerical model to calculate flutter critical wind speed of Great Belt East Bridge and Tacoma Narrows Bridge. According to time histories of vertical displacements and torsional displacements, we can judge flutter critical wind speed and flutter modality. It is critical flutter wind speed when the main beam start divergence vibration under a certain wind speed.
2 NUMERICAL SIMULATION

2.1 Great Belt East Bridge and Tacoma Narrows Bridge

As shown in Figure 1, Figure 2, and Figure 3, Great Belt East Bridge has a main span of 1624m. The semi-streamlined steel box deck is 31m wide and 4.34m high. Tacoma Narrows Bridge was constructed as a 1660 meter long suspension bridge with a main span of 853 meters, the third longest suspension bridge in the world at that time. The bridge deck was 11.9 meter wide, supported by two 2.45 meter deep plate girders (I-girders). At November morning 7 in 1940, a wind of 16-19m/s was blowing. The segments of the span were heaving periodically up and down in fifth antisymmetric vertical mode as much as 0.9m for about 3 hours, with oscillation frequency of 0.6-0.63Hz. At 10 clock in morning, one middle girder suspender root breaking, suddenly antisymmetric vertical vibration change into the antisymmetric torsional vibration, frequency is 0.23Hz, soon after, change to 0.2Hz, amplitude is bigger and bigger (approximately 8 meters), until the deck began to sway with an amplitude of about 45 degree, suspenders break, bridge deck steel fracture and ruined, falling to the valley\[1\]\[2\].

![Figure 1. Great Belt East Bridge](image1) ![Figure 2. Tacoma Narrows Bridge](image2)

Figure 1. Great Belt East Bridge \[1\] Figure 2. Tacoma Narrows Bridge \[2\]

Figure 3. Girder Cross-sections(m)

2.2 Numerical simulation principle

The structure is regarded as mass, spring and damping system. Schematic diagram of numerical simulation is shown in Figure 4. The governing structural equation for the one-degree-of-freedom heaving mode and torsional mode is shown as (1), (2).

![Figure 4. Schematic diagram of numerical simulation](image3)
\[ m\ddot{y} + c_h\dot{y} + k_hy = F_h \] (1)

\[ I_\theta \ddot{\theta} + c_\theta \dot{\theta} + k_\theta \theta = M_\theta \] (2)

Where \( m \) is the mass per unit length of the body, \( I_\theta \) is the mass moment of inertia, \( k_h \) is the translational spring stiffness, \( k_\theta \) is the rotational spring stiffness, \( c_h \) and \( c_\theta \) is the structural damping coefficients, \( F_h \) and \( M_\theta \) is the fluid forces. \( y \) denotes the transverse location of the centre of the body and \( \theta \) denotes the rotational angle of the body around elastic centre.

The governing equations of the incompressible flow is the continuity equation and the Navier-Stokes equations as (3),(4).

\[ \nabla \cdot \vec{V} = 0 \] (3)

\[ \frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla)\vec{V} = -\frac{1}{\rho} \nabla p + \mu \nabla^2 \vec{V} \] (4)

Where \( \rho \) is the density of the fluid. \( \vec{V}, p, t \) denote the velocity vector, pressure, time respectively.

Solve equation (3),(4), obtain pressure and velocity around object, calculate aerodynamic force acting on the object. This can be done by FLUENT. Then extract lift and moment into vibration equation (1) (2) and solve the vibration equation by Newmark method. The velocity is assigned to the object and simulate object move by FLUENT dynamic mesh technique. This can be done by secondary development of FLUENT which program code is embedded to the FLUENT by user defined function (UDF).

2.3 Numerical simulation model

![Figure 5. Whole mesh](image1)

![Figure 6. Local mesh](image2)
Computational grid is shown in Figure 5. and Figure 6.. The flow runs from the left to the right. The inflow boundary is specified with the inflow velocity. On the right exit boundary, it is specified with free flow. The upper and lower borders is specified with the wall. The no-slip boundary condition is employed on the body surface. Fine grid is created near the body and the grid becomes gradually coarser in the far field. Navier-Stokes equations are solved by using finite volume method, second-order upwind difference form and SMPLEC algorithm. RNG turbulence model is used in Great Belt East Bridge and the LES turbulence model is used in Tacoma Narrows Bridge. Properties of the suspension Bridge is shown in Table 1.

Table 1. Properties of the suspension Bridge\(^{[3][4]}\)

<table>
<thead>
<tr>
<th>parameters</th>
<th>unit</th>
<th>Great Belt East Bridge</th>
<th>Tacoma Narrows Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per unit length</td>
<td>kg/m</td>
<td>23687</td>
<td>4250</td>
</tr>
<tr>
<td>Mass moment of inertia</td>
<td>kgm/m</td>
<td>2.501x10^6</td>
<td>177730</td>
</tr>
<tr>
<td>Natural vertical frequency</td>
<td>Hz</td>
<td>0.097</td>
<td>0.13</td>
</tr>
<tr>
<td>Natural torsional frequency</td>
<td>Hz</td>
<td>0.27</td>
<td>0.2</td>
</tr>
<tr>
<td>vertical damping ratio</td>
<td>/</td>
<td>/</td>
<td>0.005</td>
</tr>
<tr>
<td>Torsional damping ratio</td>
<td>/</td>
<td>/</td>
<td>0.005</td>
</tr>
</tbody>
</table>

The vertical damping ratio and torsional damping ratio of Great Belt East Bridge are $1.59 \times 10^{-3}$ and $3.18 \times 10^{-4}$ respectively in the paper.

3 NUMERICAL SIMULATION RESULTS

3.1 The Great Belt East Bridge

3.1.1. Time histories of Lift coefficient and moment coefficient

(1) $v=60\text{m/s}$

(2) $v=63\text{m/s}$
As shown in Figure 7. and Figure 8., we can see the force acting on the deck at different wind speed. When the wind speed is 60 m/s, the force acting on the deck gradually decreased. When the wind speed is 63 m/s, the force acting on the deck remain almost same. When the wind speed is 65 m/s, the force acting on the deck gradually increased.

3.1.2 Time histories of displacements

![Figure 9. Time histories of vertical displacements](image)

![Figure 10. Time histories of torsional displacements](image)
Figure 9. and Figure 10. show the displacements change of deck at different wind speed. When the wind speed is 60 m/s, vertical and torsional displacements gradually decreased. When the wind speed is 63 m/s, vertical and torsional displacements remain almost same. When the wind speed is 65 m/s, vertical and torsional displacements gradually increased. Divergent coupling vibration between vertical-bending model and torsional mode of deck is found when the wind speed is over 63 m/s. Vertical vibration frequency and the torsional vibration frequency are about 0.2 Hz, which is between the vertical and torsional natural frequencies. As shown in Table 2., critical wind speed of flutter by numerical simulation is in agreement with wind tunnel testing.

Table 2. Critical wind speed of flutter [3]

<table>
<thead>
<tr>
<th>source</th>
<th>critical wind speed of flutter (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wind tunnel testing (section model)</td>
<td>74</td>
</tr>
<tr>
<td>numerical simulation</td>
<td>63—65</td>
</tr>
</tbody>
</table>

3.1.3. Contours of vorticity magnitude at different times

(1)  
(2)  
(3)  
(4)  
(6)  
(7)  
(8)  
(9)
Figure 11. Contours of vorticity magnitude at different times

As illustrated in Figure 11., we can see the movement of object is driven by vortex. Rotate clockwise and drift along the lower part of the main beam, main beam rotate counterclockwise, vortex rotate counterclockwise and drift along the upper part of the main beam, main beam clockwise torsion. The interaction between the main beam and vortex motion lead to divergent vibration.

3.2 Tacoma Narrows Bridge

3.2.1 Time histories of Lift coefficient and moment coefficient

Figure 12. Time histories of Lift coefficient  Figure 13. Time histories of moment coefficient
As shown in Figure 12. and Figure 13., We can see the force acting on the deck at different wind speed. When the wind speed is 8m/s, the force acting on the deck remain almost same. When the wind speed is 10m/s or 12m/s, the force acting on the deck gradually increased.

3.2.2 Time histories of displacements

![Graphs showing time histories of displacements for different wind speeds](image)

Figure 14. Time histories of vertical displacements
Figure 15. Time histories of torsional displacements

Figure 14. and Figure 15. shows the beam displacement under different wind speeds. When the wind speed is 8m/s, vibration is limit, vertical displacement does not exceed 0.4m, torsional angles degree is less than 1 degrees; When the wind speed is 10m/s, The maximum vertical displacement is 0.4m, The maximum torsion angle is above 5 degree and increases with time; When the wind speed is 12m/s, torsional vibration divergence is evident. the oscillation frequency is 0.2Hz, the same as torsional frequency of the structure. As Table 3. shows, Critical wind speed of flutter by numerical simulation is in agreement with wind tunnel test.

<table>
<thead>
<tr>
<th>result</th>
<th>Tacoma Narrow Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>wind tunnel test</td>
<td>11.5</td>
</tr>
<tr>
<td>numerical simulation</td>
<td>8—10</td>
</tr>
</tbody>
</table>

Table 3. Critical wind speed of flutter(m/s) [4]
3.2.3. Contours of vorticity magnitude at different times

Figure 16. Contours of vorticity magnitude at different times
As illustrated in Figure 16., it is noted that H shaped section movement is drive by vortex. Vortex is generated by upstream end and continuous development, movement, The vortex experienced a complete cycle from developing, moving and ultimately shedding. Actions on structures also completed a cycle of evolution. If we effectively prevent the large-scale vortex formation, twisting instability can be controlled in a certain extent. Tacoma bridge girder design is obvious defect: width span ratio of the stiffening beam is small, torsional rigidity is weak, On both sides there is windtight bluff body longeron, It is easy to cause the aeroelastic instability. So we might increase the cross-sectional size to get sufficient torsional rigidity and adopts a streamline cross section shape and ventilated structure to prevent large vortex formation.

4 CONCLUSION

By numerical simulation analysis can we get the following conclusions:
(1) Critical flutter wind speed by numerical simulation is in agreement with wind tunnel test.
(2) Bending-torsional coupled flutter is found in Great Belt East suspension bridge. Flutter frequency is between the vertical natural frequency and torsional natural frequency of structure. Torsional domined flutter is found in Tacoma Narrow Bridge. Flutter frequency is the same as torsional natural frequency of structure.
(3) The interaction between the main beam and vortex motion is one of the reasons leading to divergent vibration.

5 REFERENCES