ESTIMATION OF AERODYNAMIC ADMITTANCE BY NUMERICAL COMPUTATION

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Abstract. The present study describes the evaluation using numerical computations of gust forces acting on bridge decks. When predicting the gust response of long span bridges the gust response analysis in frequency domain has been widely used. In order to improve the accuracy of the computation, it is important to provide the aerodynamic admittance and spanwise correlation of wind force with high accuracy. Using CFD based on a two-dimensional RANS, the lift forces acting on several basic cross-sections in turbulent flow were evaluated. First of all, the proposed computation method was validated by the calculation of a thin plate of which gust force has been established by aerofoil theory. Then the aerodynamic admittances of a rectangular section of B/D=5 and a shallow hexagonal section were calculated. Computation results were in good agreement with experimental results of the previous study.
1 INTRODUCTION

When evaluating the gust response of a bridge using gust response analysis in frequency domain, aerodynamic admittance functions for the bridge deck and other members need to be defined. The aerodynamic admittance function of a bridge deck depends on its cross section[1][2], because the gust force acting on the bridge deck is generated not only from approaching gusty wind but also from the separated flow inherent in the geometry of the deck cross section. A wind tunnel test is carried out for each cross section in the usual way to evaluate the gust force, however, it is time-consuming and costly.

Lots of efforts have been made on points of applicability of CFD to wind resistant design for structures. As for bridges, the estimation of flutter derivatives or steady aerodynamic force coefficients of decks has been investigated as an alternative to preliminary wind tunnel tests[3][4]. On the other hand, there are very few investigations on applications to gust force in turbulent flow.

In this paper, the estimation procedure of the aerodynamic admittance function is discussed. The aerodynamic admittance functions of several cross sections were calculated and were compared with wind tunnel test results.

2 NUMERICAL METHOD[4]

The two-dimensional incompressible Navier-Stokes equations were used as the governing equations. The numerical algorithm was based on the method of pseudocompressibility[5]. The convective terms were discretized by the fifth-order upwind differential scheme and the implicit method of second-order was employed as a time integration algorithm. The k-ω SST turbulence model[6] was used. An overset grid system was used in the present computation where an O-type grid around the body was overlapped on a background grid of H-type as shown in Fig.(1).

This paper focuses on lift fluctuation in the vertical gust. At the inlet boundary of the computational domain, the vertical gust was generated by controlling the inflow angle. At inlet boundary, the specific dissipation rate $\omega_\infty$ and the eddy viscosity coefficient $\nu_\infty$ were set as

$$\omega_\infty = \frac{U_\infty}{B}, \quad \nu_\infty = 10^{-3} \nu_\infty$$

where, $U_\infty$ is the mean flow velocity, B is the width and $\nu_\infty$ is the kinematic viscosity at the inlet boundary. The Reynolds number ($R_e = U_\infty B / \nu_\infty$) was set as 140,000 for all computations. Thus the turbulent kinetic energy $k_\infty$ is given as follows:

$$k_\infty = \nu_\infty \omega_\infty = 10^{-3} \nu_\infty \cdot \frac{U_\infty}{B} = 10^{-3} R_e^{-1} U_\infty^2 \approx 10^{-8} U_\infty^2$$

Then, $\sqrt{2k_\infty}$ is sufficiently small compared to velocity fluctuations due to purposely-generated gust. Values of $k$ tended to be large in boundary layers or separated flow regions on the body, however, in the regions $\omega$ which had dimensions (time)$^{-1}$ was sufficiently high compared to the relevant frequency range within which natural frequencies of structures fall. Actually, in the present computations, values of $\omega$ in the region were two orders of magnitude higher than the significant frequency range relevant to the gust response analysis. Therefore, the gust force properties of decks could be evaluated only from the unsteady solution of mean-flow equation without taking into account the turbulent kinetic energy $k$ obtained from calculations.
3 CALCULATION CONDITIONS

3.1 Turbulent Characteristics of Generated Flow

The preliminary computations were performed to assure the accuracy of computed gusts. Fig.(2) shows the time histories of velocity fluctuations computed on the condition that the sinusoidal gusts are provided as inflow turbulence and no body is placed in the flow field. The amplitude of the wind inclination angle at the inlet boundary is 2.0 degrees. Then it is equivalent to turbulent intensity of 2.2%. As the amplitude of the wind inclination is sufficiently small, the solution is expected to approach to the theoretical solution of the linear wave equation and the gust pattern is to move past without changing its wave shape. From an examination of Fig.(2), it is found that we should set two parameters suitably, the height of the computational domain and $\Delta tU/B$. In this investigation the height of the computational domain was set at 60B to weaken the effect of the slip walls at the upper and lower boundaries particularly in low frequency regions. For low frequency waves, time steps were not crucial and relatively large time steps could be taken. In high frequency regions, however, even a relatively small time step could somewhat damp and diffract waves (Fig.2(4)). Employing a smaller time step prolongs the computational time. Considering a trade-off between computational efficiency and accuracy, we set the time step $\Delta tU/B$ at 0.01 in the present computations.

Next, we tried to generate the random vertical gust which had the power spectrum of the Karman type and had almost the same turbulence intensity as the sinusoidal gust described above. As shown in Fig.(3), the power spectrum of the generated random gust agreed well with the target except in the high frequency region.
Figure 2: Time histories of the vertical sinusoidal gust obtained at (x,y) = (2B,0), No body in the field

(1) k=0.16, Domain Height = 20B, dt=0.01
(2) k=0.16, Domain Height = 60B, dt=0.01
(3) k=3.0, Domain Height = 60B, dt=0.01
(4) k=6.0, Domain Height = 60B, dt=0.01
(5) k=6.0, Domain Height = 60B, dt=0.005

Figure 3: Power spectrum of the random vertical gust at (x,y) = (2B,0), b=B/2
### 3.2 Computational Case

Three basic cross sections shown in Table 1 were addressed. Two kinds of turbulent flows, random vertical gusts and sinusoidal gusts, were employed for evaluation of the aerodynamic admittance function of the cross sections.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Surrounding</th>
<th>Background</th>
<th>Time step (ΔtU/B)</th>
<th>Reynolds Number (Re=UB/ν)</th>
<th>Turbulent Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>B/D=200</td>
<td>285×83</td>
<td></td>
<td>0.01</td>
<td>1.4×10^5</td>
<td>Random gust : Iu &lt; 0.1%, Iw = 2.1%</td>
</tr>
<tr>
<td>B/D=5</td>
<td>293×45</td>
<td></td>
<td></td>
<td></td>
<td>Sinusoidal gust : Iu &lt; 0.1%, Iw = 2.2%</td>
</tr>
<tr>
<td>Hexagonal</td>
<td>265×43</td>
<td>294×459</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Computational case

### 4 AERODYNAMIC ADMITTANCE

#### 4.1 Derivation Method of Aerodynamic Admittance

In the case of lift forces, the power spectrum can be expressed by

\[
S_L(\omega) = \left( \frac{1}{2} \rho U^2 b \left( \frac{dC_L}{d\alpha} + C_d \right) \right)^2 |X_L(\omega)|^2 \frac{S_u(\omega)}{U^2}
\]

Where, \( S_u(\omega) \) is the spectrum of the lift force, \( \rho \) is air density, \( b \) is the half chord length, \( |X_L(\omega)| \) is aerodynamic admittance, \( dC_L/d\alpha + C_d \) is the derivative of lift force coefficient with respect to the angle of wind incidence.

The aerodynamic admittance was assessed directly from power spectrums of the lift forces in the generated gust and velocity at the assumed position of the body obtained from the computation performed beforehand for free-field without the body. The \( dC_L/d\alpha + C_d \) under the smooth flow condition was also calculated beforehand.

#### 4.2 Aerodynamic Admittances of The Basic Cross-Sections

Fig.(4) shows vertical velocity of generated gust and lift force coefficients in the same period of time. Obtained unsteady lift force consists of two different wave patterns, that is to say, the lift fluctuation caused by the variation of incident angle and the periodic shedding of vortices. It is found that the gust force characteristics depend considerably on cross-section shape.

The aerodynamic admittance function of each cross section was evaluated based on these data. First of all, the computational method described above was validated through the calculation of a thin plate whose aerodynamic property has been established by the aerofoil theory. A rectangular section of B/D =200 was employed as a thin plate in the present computation.
Fig. (5) shows the computed result of the aerodynamic admittance function together with the Sears Function. These two are found to agree with each other well. In addition, it is clarified that aerodynamic admittance functions in random gust and sinusoidal gust also correspond with each other. This means that superimposition is applicable in estimating gust forces in relatively small flow fluctuation.

As for the rectangular section of \( B/D = 5 \) and hexagonal cross section, the feature of aerodynamic admittance simulated by the present computation is found to agree well with the wind tunnel test results\(^7\) obtained in two-dimensional turbulent flow. The reduced frequency at the highest peak of each cross-section corresponds with the Strouhal number.

![Wind Velocity and Lift Forces](image)

Figure 4: Time histories of fluctuations of wind velocity and lift forces
5 FLOW PATTERNS AROUND THE CROSS SECTIONS

In order to discuss the difference of aerodynamic admittance in deck configurations, the flow pattern around the each cross section was examined. Typical instantaneous flow patterns at the moment that the upward and downward lift are at the maximum are shown in Fig.(7). In these figures, the distributions of velocity vector and nondimensional pressure $C_p = p/(0.5\rho U^2)$, where $p$ is instantaneous pressure, are indicated by arrows and the shade of gray, respectively.
As for the thin plate of B/D=200, a thin separated shear layer can be observed in a small area around the leading edge on the upper surface when the flow is blowing up. On the other hand, it is found that the massive separated shear layer is formed and that the flow reattached near the trailing edge in the case of B/D=5. The reattach point tends to move back and forth synchronously with vertical fluctuation of flow.

Fig.(8) shows the distributions for various reduce frequencies of unsteady pressures along the surfaces of the cross-sections in the sinusoidal gusts, the magnitudes of pressure fluctuations and the phase lags between the wind velocities at the leading edge and the pressures at the points on the surfaces. In general, it is found that the hexagonal section has the similar pressure distribution to the thin plate of B/D=200, that is to say, only the narrow region around the leading edge is dominant in the formation of unsteady lift force, and the phase lag tends to be flat except around the trailing edge in both cross-sections.

As for the rectangular section of B/D=5, the magnitudes of the pressure fluctuations is relatively large in a wide region which corresponds to the separated flow region shown in Fig.(7). The separated flow region which expands and contracts in sync with vertical gust tends to amplify the fluctuating lift force. As a result, its aerodynamic admittance differs from the Sears Function.
Figure 8: Unsteady pressure distribution along the surface of the cross sections in the sinusoidal gust, magnitudes of unsteady pressure ($C_{pd}$) and phase lags between the wind gust at the leading edge and the pressures

6 CONCLUSIONS

- Aerodynamic admittances due to vertical wind gust for basic cross-sections were evaluated by computation based on the two-dimensional RANS. The aerodynamic admittance for a thin plate of B/D=200 predicted by the present computations agreed well with the Sears Function. As for the rectangular and hexagonal sections, the calculation results
agreed well with an experimental result, too. The present method seems like a promising tool for predicting gust force characteristics of bridge decks.

- The aerodynamic admittance function of a bridge deck depends on its cross section. The feature of aerodynamic admittance of the hexagonal section was in agreement with that of a flat plate. On the other hand, it was found that the separated flow from the leading edge had a great influence on the lift force property, so that there was a big difference in aerodynamic admittance between the B/D=5 and the flat plate.

REFERENCES


