Numerical simulations of a wind-induced vibrating square cylinder within turbulent boundary layer

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KEYWORDS: square cylinder, wind-induced vibration, aeroelastic, turbulent boundary layer.

1 INTRODUCTION
Wind-induced vibrations of tall buildings have been estimated using the two different types of wind tunnel experiments: “wind force experiments” and “aeroelastic experiments.” For the wind force experiments, the unsteady aerodynamic forces acting on static models are measured and then applied to external forces in the spectral modal response analyses or dynamic response analyses. Since this approach neglects motion induced wind forces, resulting wind loads fail safe as far as the aerodynamic damping becomes positive. On the other hand, the aeroelastic experiments can directly provide vibration responses. The rocking motion models are generally used for the experiments since first vibration mode is dominant with tall building responses.

The applications of Computational Fluid Dynamics (CFD) to wind-induced vibrations have been restricted to simple problems. They usually have been done with uniform laminar flows, and the whole buildings are translated into along and cross wind directions though, in fact, its basement is fixed at the ground. Fortunately, recent evolutions of CFD technique, especially those for generating turbulent boundary layer flows or for computing with moved-and-transformed grids, enable us to handle practical wind-induced vibrations.

In this paper, the author argues the numerical approaches for evaluating wind-induced vibrations of a tall building. Computational conditions and numerical methods are explained first. Then computed vibration responses obtained by “wind force computations” and “aeroelastic computations” are shown and compared. The differences between them will show the effect of motion induced wind forces. The vertical places on which the motion induced aerodynamic forces act and the effect of reduced velocity to those affected places are examined as well.

2 NUMERICAL CONDITIONS
2.1 Objective tall building
The objective tall building has a square cylinder shape and its dimensions are width \( B = 50 \text{m} \), depth \( D = 50 \text{m} \) and the height \( H = 200 \text{m} \) (aspect ratio \( H/B = 4 \)). Its mode shape is set as linear, thus the rocking motion, and cross-wind directional responses have to be considered. Other conditions of the building are listed in Table 1.

Computations are conducted in the 1/1000 model scale and Reynolds number based on \( B \) and \( U_H \) (the time-averaged inflow velocity at the cylinder’s top) is fixed as \( \text{Re} = U_H B / \nu = 2.8 \times 10^4 \). Instead of changing \( U_H \), the natural frequency \( f \) is changed in order to examine the effect of reduced velocity \( V_r = U_H / f B \) to the cylinder’s response. The design wind speed and the structural condition of the building provide a design reduced velocity as \( V_r = 4.35 \).

<table>
<thead>
<tr>
<th>Building’s conditions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building’s density ( m )</td>
<td>505.8 kg/m(^3)</td>
</tr>
<tr>
<td>Density of the air ( \rho )</td>
<td>1.225 kg/m(^3)</td>
</tr>
<tr>
<td>Damping coefficient ( h )</td>
<td>1.34 %</td>
</tr>
<tr>
<td>Natural frequency ( f )</td>
<td>0.25 Hz</td>
</tr>
<tr>
<td>Design wind velocity ( U_H )</td>
<td>54.4 m/s</td>
</tr>
</tbody>
</table>

Table 1. Building’s conditions
2.2 Numerical method

Three-dimensional Navier-Stokes equations are solved as basic equations. To couple pressure and velocity fields, the artificial compressibility approach is taken. These equations are transformed from the Cartesian coordinate to the generalized one, then discretized using a finite volume method (FVM).

The spatial derivatives and viscous fluxes are computed with a second-order central difference while convective terms are approximated by a 3rd-order upwind scheme with the size of artificial dissipation term is set as a half of UTOPIA scheme. A second-order implicit scheme is taken for temporal derivatives. For the computations with moved-and-transformed grids, the time derivatives of transformation metrics are evaluated according to its geometrical meanings in time and space dimensions. Details of the method can be seen in the reference [1].

Figure 1 shows a grid system. The domain is divided into 7 blocks. Block 1 and 7 are transformed after the cylinder’s motion for aeroelastic computations and are immobile during wind force computations. The block 6 is a driver section for generating inflow turbulence. Other boundary conditions are; a free slip boundary condition for the ceiling, a no-slip condition for the surfaces of floor and cylinder, a periodic condition for side walls of block 6 and the remainder parts of side walls are set as free-slip. The time step size is set as $\Delta t U_H / B = 0.01$.

2.3 Inflow conditions

The timeDepending inflows are generated using pseudo-periodic boundary conditions [1, 2] with which the time average velocity profile at the inlet is prescribed and fluctuating part of the velocity is recycled between the driver’s (block 6’s) extract and inlet sections.

Generated velocity profiles are shown in Figure 2 with the reference wind tunnel measurements [3]. Those values are taken at the cylinder position when the whole domain is computed.
with the cylinder filled with additional flow-computing grid points. The time averaged windward velocity $u$ and its rms value $\sigma_u$’s profiles are reproduced quite well. According to the power spectrum density curve, it follows Kármán spectrum well until $nB/U_H=0.5$ which corresponds $1/4$ of Nyquist frequency based on the grid resolution $\Delta x/B (=0.25)$ at the driver section. A small peak at $nB/U_H=0.05$ is due to the driver section’s length.

3 COMPUTED RESULTS

3.1 Overall wind force coefficients

A wind force computation is conducted first. Figure 3 shows the computed power spectrum densities of the base moment coefficients $C_{Mx}$ (rocking in cross wind direction) and $C_{My}$, (along wind direction). For the reference, densities provided by Architectural Institute Japan’s (AIJ’s) recommendations [4] are illustrated also. To obtain AIJ’s $C_{My}$ density curve, the turbulent length scale is adjusted.

The power spectrum density of $C_{Mx}$ shows its peak at a higher frequency level and a narrower shape than those of $C_{My}$. These aspects coincide with AIJ’s.

3.2 Response analyses

With the wind force computations, the rms value for displacement angle $Ay_{rms}/H$ is calculated by the spectrum modal response analysis as;

$$\frac{Ay_{rms}}{H} = \frac{3\rho B}{2mH} \frac{V_r}{\pi C_{Mx_{rms}}} \left(1 + \frac{\pi}{4h} \frac{fS(f)}{\sigma^2} \right)^{0.5}$$

(1)

where $fS(f)/\sigma^2$ corresponds the power spectrum density of $C_{Mx}$ as shown in Figure 3.

For the aeroelastic computations, the vibration responses are directly computed. Taking the flow field around a fixed cylinder at $tU_H/B=50.0$ as the initial condition, computations are continued until the response is fully developed. Figure 4 shows instantaneous vortical structures around the cylinder when it tilts toward negative y-direction. and time histories of the displacement for $V_r=19$. Since no unphysical vortical structure is seen, the computational grids and obtained flow fields seem to follow cylinder’s motion well.

Computed responses by the spectrum modal response analysis and aerodynamic computations are shown in Figure 5 with wind tunnel experiments.

Below the resonance velocity ($V_r<10.0$), the solid curve obtained by the modal response analysis traces the plots of experiments and aeroelastic
computations, but differ at the higher velocity. The motion induced aerodynamic force which neglected in the modal response analysis causes such difference. The unstable oscillations continue to develop beyond the resonance velocity \( V_r = 10.0 \) both in the aeroelastic computations and experiments.

3.3 Aerodynamic force coefficients

During the aeroelastic computations, the cross-wind directional local wind force coefficients \( C_{Fy}(z) \), are recorded at several vertical positions. Their time histories are analyzed by FFT, then its in-phase part to cylinder’s motion \( C_{Fy1}(z) \) and the phase differences at the cylinder’s oscillation frequency are computed. The distributions for \( V_r = 11 \) and 19 are shown in Figure 6. Near the resonance velocity, \( C_{Fy1}(z) \) becomes positive along all cylinder axis, namely, the negative aerodynamic damping force acts at every height \( (V_r=11) \). Its magnitude is larger in the lower part and declines toward the top. When \( V_r \) exceeds resonance velocity, on the contrary, \( C_{Fy1}(z) \) becomes negative at the lower part and has a positive peak value near the top \( (V_r=19) \). This means the vigorous oscillation is induced by the aerodynamic forces acting on the upper part. Phase differences indicate the same direction.

4 CONCLUSION

To predict the cross wind directional wind-induced vibrations of a tall building, numerical flow computations are conducted. The aeroelastic computations achieve good accordance with the experiments. The computed cross wind directional forces can provide the same spectrum shape as experiments with relative ease. The shape along wind direction, however, is highly affected by the turbulent inflow conditions. Therefore the grid resolutions at the driver section should be chosen carefully to capture higher frequency of velocity fluctuations, especially for evaluating the effect of buffeting motion to residents’ comforts.

5 REFERENCES