A NUMERICAL STUDY ON VORTEX-INDUCED VIBRATION OF A CIRCULAR CYLINDER TOWER

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ABSTRACT

A numerical simulation code is developed to study the characteristics of the vortex-induced vibration of a circular cylinder tower. A moving grid method is employed to simulate a flow around the oscillatory object. This code has the ability to analyze fluid-structure interaction phenomena by coupling a fluid analysis code with a structure analysis code. A vibration of a circular cylinder tower which allowed the vibration in transverse-to-wind direction is simulated with fluid-structure coupled analysis. As a result of the simulation, the vortex-induced vibration occurs in case of reduced wind speed $V_r = 6$. Moreover, another vibration occurs in case of reduced wind speed $V_r = 14$. These results show good agreement with the experimental results of Kitagawa et al. (1999).

INTRODUCTION

A vibration of a circular cylinder which is placed in a flow occurs around a certain wind speed, and the vibration is caused by the Karman vortex. This vibration is called the vortex-induced vibration (VIV). VIV occurs because the vortex-shedding frequency coincides with one of the natural frequencies of the structure. As for the vortex-induced vibration, the phenomena have been clarified by many experimental and analytical studies.

On the other hand, some experimental studies using a cantilevered circular cylinder indicate that not only VIV but also a vibration similar to vortex-induced vibration occurs at a wind speed which is a few times higher than the onset wind speed of VIV. This vibration is called the "end-cell-induced vibration (ECIV)" by Kitagawa et al. (1999). ECIV seems to be induced due to the flow influenced by the tip of the cylinder but the phenomena have not been sufficiently clarified.

Wootton (1969) carried out wind tunnel experiments using circular stack models and measured the transverse-to-wind response, which indicated the occurrence of ECIV at a wind speed twice as high as VIV-onset wind speed. He described that the cause of ECIV was associated with the flow around the tip of the model, but no evidence was shown.

Kawai (1994) conducted wind tunnel experiments using circular cylinder rocking models and obtained not only the response of the ordinary VIV but also the response of ECIV at a wind speed 2.5times higher than the onset wind speed of VIV. In the power spectra of the transverse-to-wind response, a peak due to the aerodynamic force whose frequency was lower than the Karman Vortex shedding frequency appeared.

Kitagawa et al. (1998) conducted wind tunnel experiments using a circular cylinder rocking model. The transverse-to-wind response and the wind velocity fluctuations behind the model at various heights were measured. It was shown that the response peak due to ECIV could be observed under a uniform flow. The power spectra of the wind velocity fluctuations behind the model indicated that a fluctuation which was not caused by the Karman vortex was generated around the free-end. With these results, Kitagawa et al. inferred that ECIV was induced by the tip-associated vortices.

In this report, in order to study the mechanism of ECIV, a numerical simulation code is developed and some numerical simulations are carried out. The results of the simulation are compared with the experimental data of Kitagawa et al. (1999).

GOVERNING EQUATIONS

The governing equations of the present simulations are three-dimensional compressible Navier-Stokes equations. No turbulence model is used in the present simulation. The governing equations are discretized using Finite Volume Method.

NUMERICAL METHOD

As the numerical fluid analysis technique, TVD scheme which combined MUSCL interpolation and Roe's Flux Difference Splitting (Roe, 1981) is employed. 1st-order implicit time integration which combined Newton iterative method and Gauss-Seidel relaxation scheme is employed for unsteady flow analysis. By employing the multi-block structured grid, flow analysis around a complicated shape becomes possible. Moreover, a moving grid system with GCL method (Thomas et al., 1979) is employed to analyze a flow around the oscillatory object. In order to simulate fluid-structure interaction, the fluid analysis code and a structure analysis code are coupled. In the case of fluid-structure interaction analysis, the fluid analysis and the structure analysis are carried out alternately. As the structure analysis technique, Finite Element Method (FEM) is employed. The beam element of FEM is employed in order to apply the present technique to a tower shaped structure.

ANALYTICAL CONDITIONS

An analytical model is set according to the experimental model of Kitagawa et al. (1999). As shown in Figure 1, a circular cylinder tower model is used. The model is allowed the vibration in transverse-to-wind direction. The height of the cylinder, H_c, is 1250mm, and the diameter, D_c, is 50mm. The total mass of the cylinder part is 760g. The natural frequency f_n is 6.4Hz. For structure analysis, two beam elements are used. One element is modeled for the leaf-spring and the other element is modeled for the rigid cylinder. In this structure analysis model, structural damping is not used.

Analytical conditions for fluid analysis are summarized in Table 1.

Table 1: Analytical conditions

Inflow Mach number	0.1
Reynolds number	3.3×10^4
Reduced wind speed	2,6,10,14,17

The grid system for the fluid analysis is shown in Figure 2. The grid used here is a structured one; H-type in the span direction and O-type in the radius direction with the size of 121x91x91. The grid is transformed according to the structure analysis result at each time step.

RESULTS AND DISCUSSIONS

The relationship between reduced wind speed V_r ($=V/f_nD_c$, V : wind speed) and normalized (r.m.s.) displacement of the cylinder y/D_c is shown in Figure 3. This figure contains both of the experimental results and the computational results. The computational results and the experimental results are in very good agreement. In both of the computational results and the experimental results, the vortex-induced vibration (VIV) occurs at V_r=6, and the end-cell-induced vibration (ECIV) occurs at V_r=14. With these results, it was proved that the developed code is able enough to analyze fluid-structure interaction problem of a cylinder.

Iso-surfaces of vorticity around Z-axis are shown in Figure 4. The figure shows the Karman vortex shedding from the mid-span of the cylinder, and also shows the other vortex shedding from the top of the cylinder.

The time histories of the transverse-to-wind response are shown in Figure 5. The amplitude of VIV at V_r=6 is nearly constant. On the other hand, ECIV at V_r=14 has an unsteady amplitude. It is possible that the unsteady amplitude of ECIV is due to intermittent generation of the tip-associated vortices.

CONCLUSIONS

A fluid-structure coupled analysis code was developed to study the vortex-induced vibration of a circular cylinder tower. Besides, some numerical simulations were carried out to verify the accuracy of the code. The computational results for the relationship between reduced wind speed and transverse-to-wind response of a cantilever circular cylinder showed good agreement with experimental results of Kitagawa et al. (1999). Specifically, the vortex-induced vibration and the end-cell-induced vibration were simulated by this code. The authors intend to investigate the occurrence mechanism of the end-cell-induced vibration in future study.

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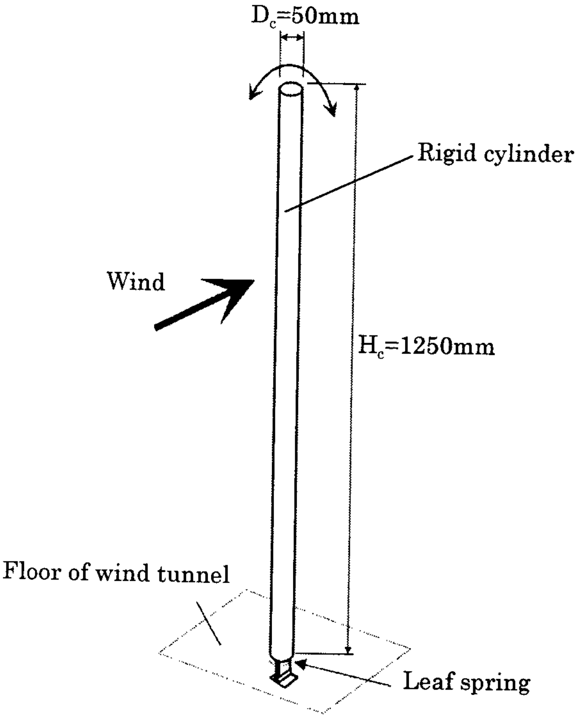
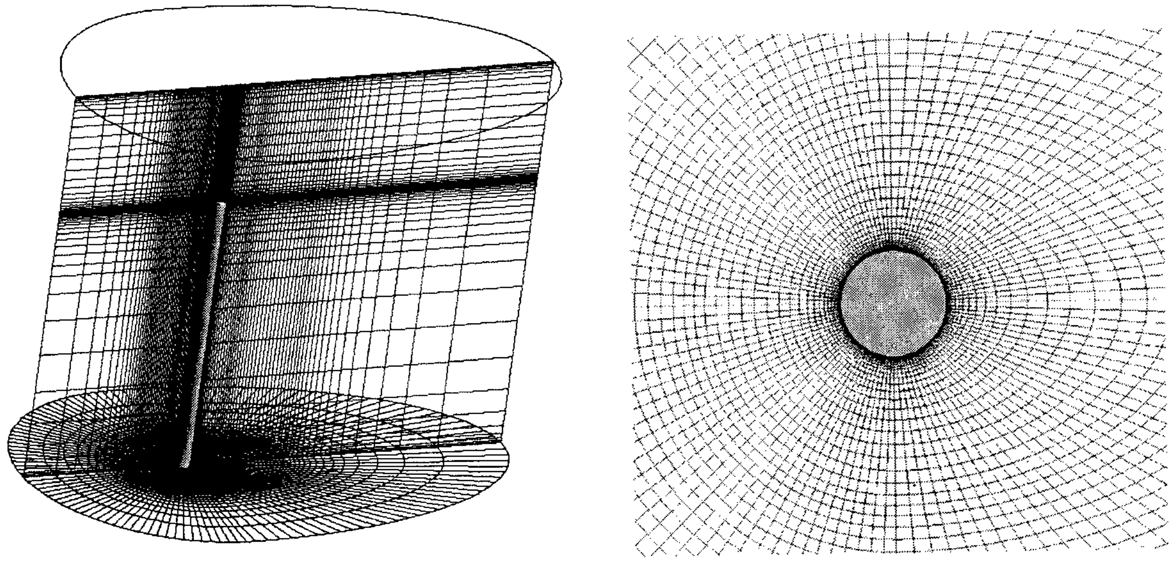


Figure 1. Experimental model (Kitagawa et al.,1999)



(a) Whole grid (b) Grid around the cylinder

Figure 2. Computational grid

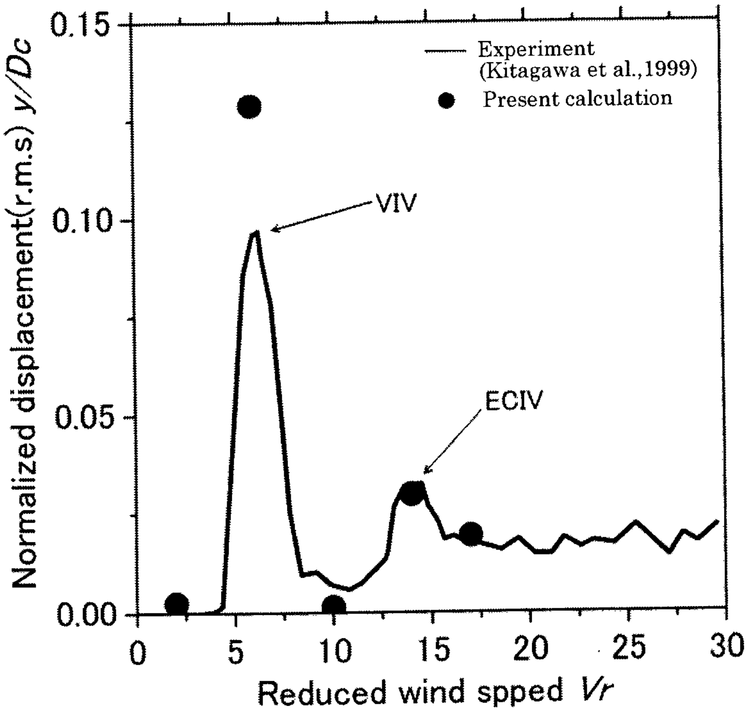
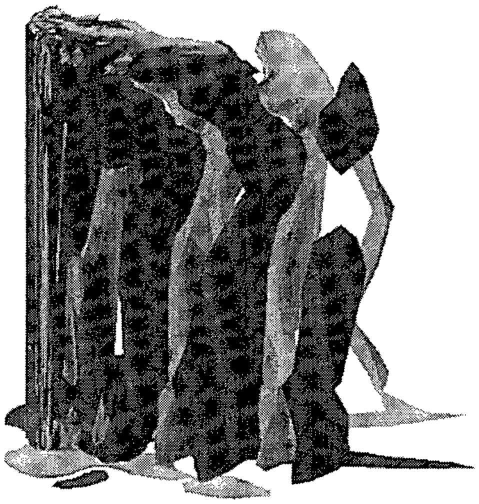
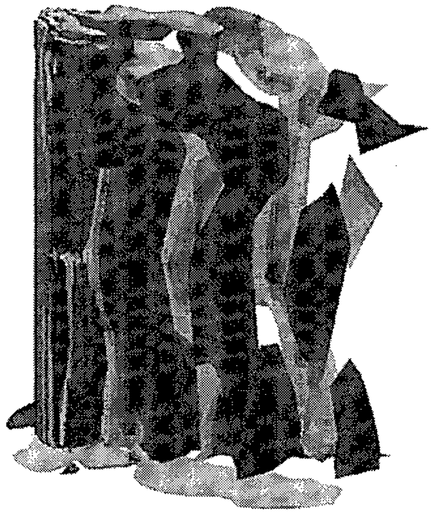


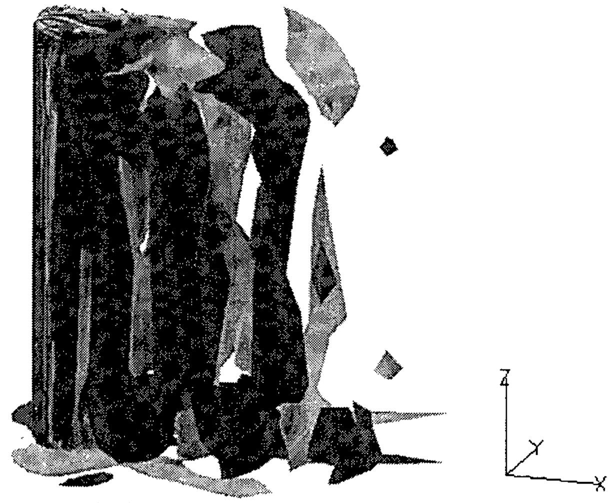
Figure 3. Transverse-to-wind (r.m.s) displacement of the cylinder, y/D_c, versus reduced wind speed, V_r



(a) $V_r = 2.0$

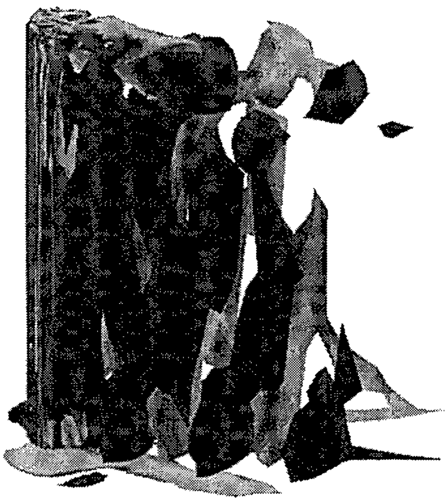


(b) $V_r = 6.0$



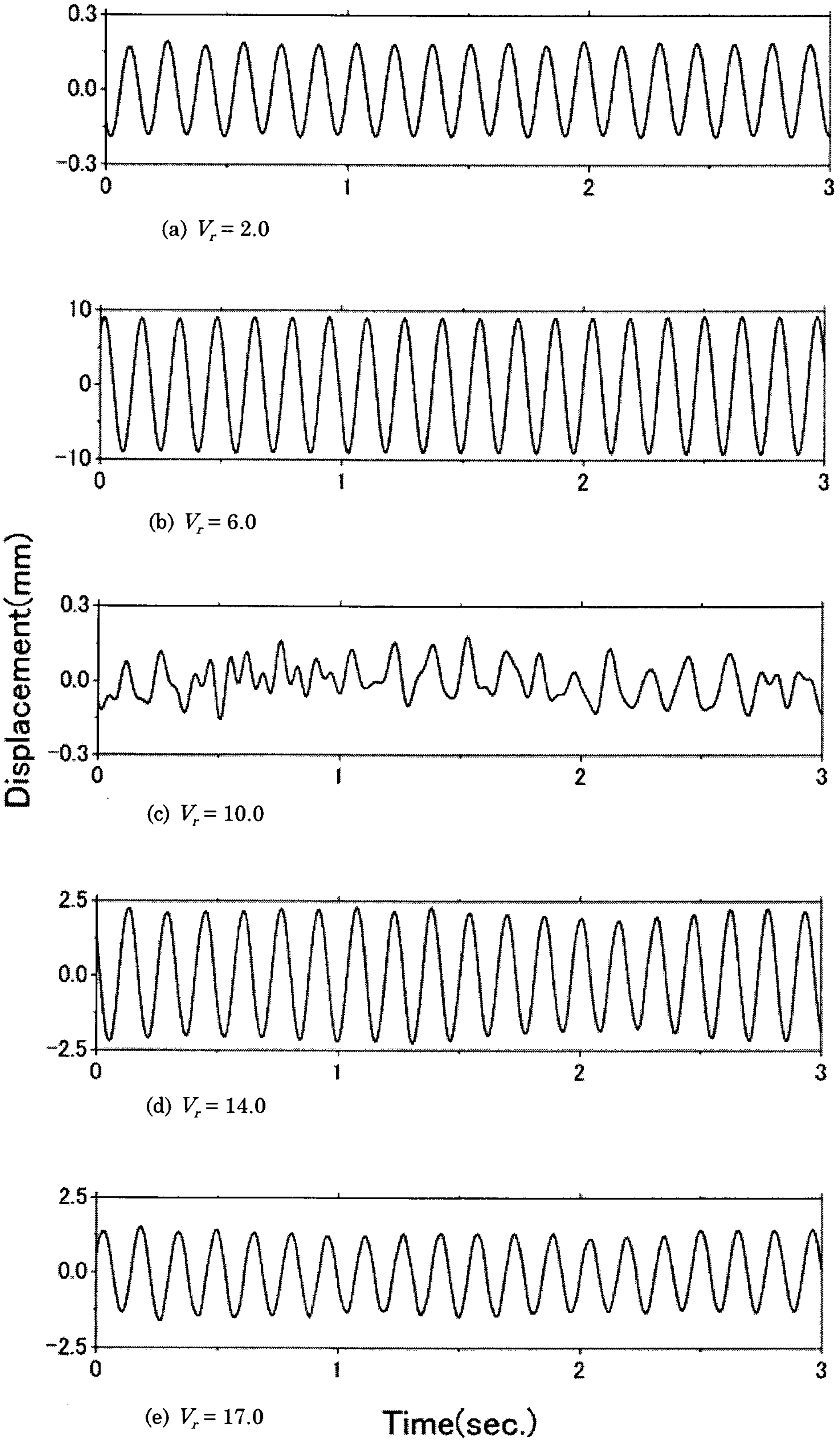
(c) $V_r = 10.0$

(d) $V_r = 14.0$



(e) $V_r = 17.0$

Figure 4. Iso-surface of vorticity around Z-axis



(a) $V_r = 2.0$

(b) $V_r = 6.0$

(c) $V_r = 10.0$

(d) $V_r = 14.0$

(e) $V_r = 17.0$

Figure 5. Time histories of the transverse-to-wind response