Numerical Investigation on the Aeroelastic Instability of Bluff Cylinders

T. TAMURA
Ohsaki Research Institute of Shimizu Corporation,
2-2-2, Uchisaiwai-cho, Chiyoda-ku, Tokyo 100, Japan
Y. ITOH and A. WADA
Tokyo Institute of Technology,
4259, Nagatsuta-cho, Midori-ku, Yokohama-shi, Kanagawa 227, Japan
K. KUWAHARA
The Institute of Space and Astronautical Science,
3-1-1, Yoshinodai, Sagamihara-shi, Kanagawa 229, Japan

Abstract

We numerically investigate the aeroelastic instability of an elongated rectangular cylinder. Through the comparison between three-dimensional computational results for the fixed and the forced-oscillating rectangular cylinders, it is confirmed the flow structure around the oscillating cylinder becomes two-dimensional in the spanwise direction. Then, on the basis of the two-dimensional simulations, we discuss the aeroelastic characteristics on the free oscillation of a rectangular cylinder in uniform flows.

1. INTRODUCTION

For the understanding of fundamental aspects about the aeroelastic instability of bluff cylinders, the computational approach is promising. Because it is easy to get the information about the interactive behavior between unsteady flows and dynamic motions of elastic cylinders. Thus far we have computed the three-dimensional incompressible flows around a square cylinder at rest and its aerodynamic characteristics have been clarified[1]. We also simulated the two-dimensional unsteady flows around a forced-oscillating rectangular cylinder in a heaving and a torsional mode[2]. Here we apply the direct finite difference technique of the three-dimensional incompressible Navier-Stokes equations to the unsteady problems on elongated rectangular cylinders. For the convection terms, the third-order upwind scheme is incorporated and no turbulence model is employed. We use the moving grid system[3] for the oscillation of a cylinder. First, we examine the necessity of the three-dimensional simulation of the aeroelastic problem. The comparison between the three-dimensional computational results of the fixed and the forced-oscillating bluff cylinders is carried out. Next, in order to investigate the aeroelastic behavior of bluff cylinders, we perform the two-dimensional simulations about the free vibration of an elastically mounted rectangular cylinder. Through the comparison with the experimental data, the vortex-induced instability of rectangular cylinders is also investigated.

2. PROBLEM FORMULATION

The governing equations are given by the following continuity and Navier-Stokes equations:

$$\mathrm{div}\,\mathbf{u} = 0, \tag{1}$$

$$\partial\mathbf{u}/\partial t + \mathbf{u}\cdot\mathrm{grad}\,\mathbf{u} = -\,\mathrm{grad}\,p + 1/Re\,\Delta\,\mathbf{u}, \tag{2}$$

where $\mathbf{u}$, p, t and Re denote the velocity vector, pressure, time and the Reynolds number respectively, non-dimensionalized by U_0 (reference velocity), B (reference length), ρ (density) and ν (kinematic viscosity).

In order to overcome the numerical instability at high Reynolds numbers, the third-order upwind scheme is employed for the nonlinear convection terms[4].

$$\left(u\frac{\partial u}{\partial x}\right)_i \approx u_i \frac{-u_{i+2} + 8(u_{i+1} - u_{i-1}) + u_{i-2}}{12\delta x} + |u_i| \frac{u_{i+2} - 4u_{i+1} + 6u_i - 4u_{i-1} + u_{i-2}}{4\delta x}, \tag{3}$$

where δx is the grid spacing. The numerical procedures are based on the MAC method[5]. The pressure field is determined by solving the Poisson equations and the velocity field is computed by the temporal integration of the Navier-Stokes equations.

For the motion of a body, the moving grid system is incorporated. A time-space($2D$) transformation of $(t, x, y, \ldots)$ to $(\tau, \xi, \eta, \ldots)$ is imposed to the original governing equations. The two-dimensional acceleration term is represented as follows:

$$\begin{aligned}&\partial_t + u\partial_x + v\partial_y = \\ &\quad \partial_\tau + \frac{1}{J}\left[(u - x_\tau)\,y_\eta - (v - y_\tau)\,x_\eta\right]\partial_\xi + \frac{1}{J}\left[-(u - x_\tau)\,y_\xi + (v - y_\tau)\,x_\xi\right]\partial_\eta,\end{aligned} \tag{4}$$

where J is the Jacobian. This relation means that the convection velocity in the computational domain is replaced by the relative velocity with respect to the moving coordinate. It should be noted that the grid system is moving in the physical domain, but stationary in the computational domain.

3. COMPUTATIONAL MODEL

Figure 1 shows a computational model where a rectangular cylinder with the depth-breadth ratio(D/B, D:the depth of a cylinder, B:the breadth) equal to 5.0 is placed in the computational domain(the diameter=$60B$). The grid of 400×100×40=1,600,000 points is used for the three-dimensional model at the Reynolds number equal to 10^4. The approaching flow is assumed to be uniform(U_0). For the boundary condition of the pressure around the computational domain, the Dirichlet condition is imposed. On the surface of a cylinder, the velocity of moving grid at boundary is given and the Neumann condition is employed for pressure.

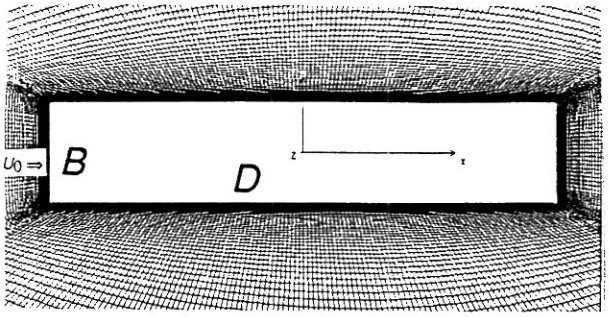


Fig. 1 Grid system for a rectangular cylinder (D/B=5.0, 400×100×40).

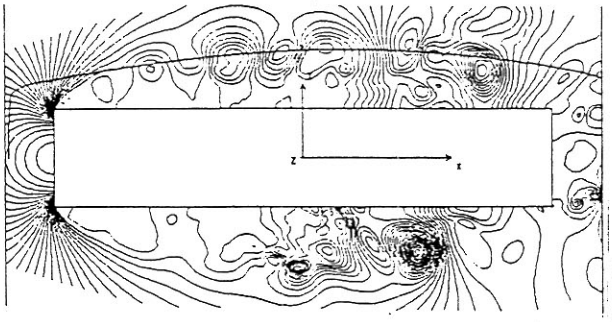


Fig. 2 Instantaneous pressure contours around the cylinder at rest.

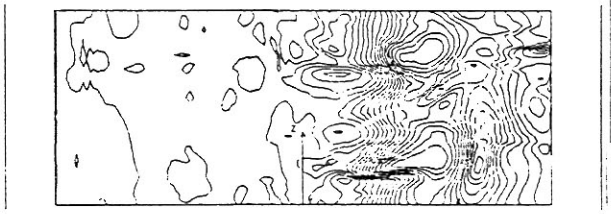


Fig. 3 Instantaneous pressure contours on the side surface of the cylinder at rest.

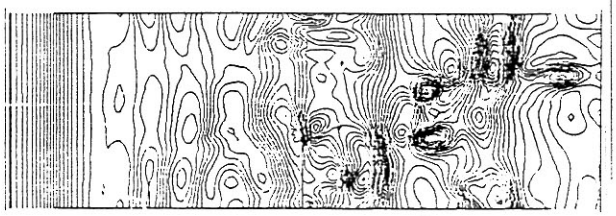
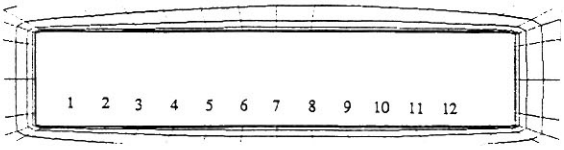
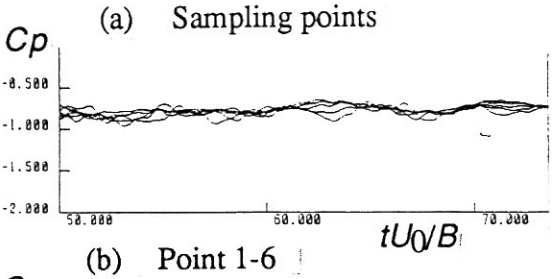


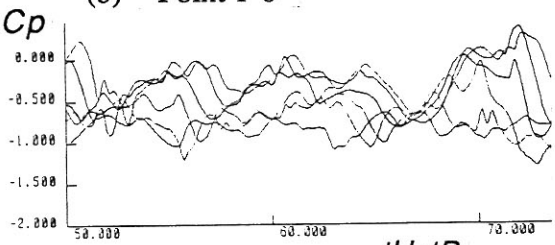
Fig. 4 Instantaneous pressure contours on the spanwise section along the separated shear layer (See Fig. 2).



(a) Sampling points



(b) Point 1-6



(c) Point 7-12

Fig. 5 Time variation of pressure coefficients.

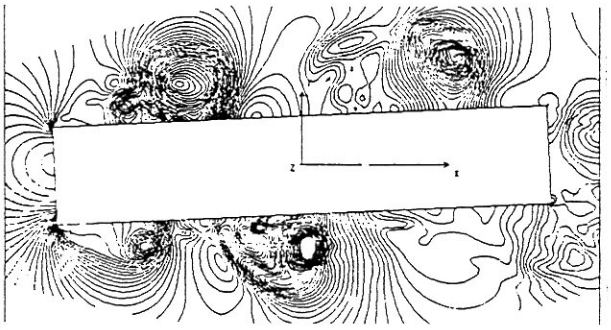


Fig. 6 Instantaneous pressure contours around the forced-oscillating cylinder (Re=10^4, Vr=5.0, θ_0=5°).

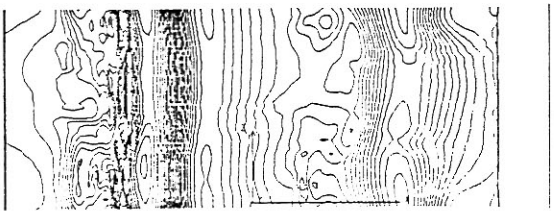


Fig. 7 Instantaneous pressure contours on the side surface of the forced-oscillating cylinder (Re=10^4, Vr=5.0, θ_0=5°).

4. THREE-DIMENSIONAL SIMULATIONS FOR A RECTANGULAR CYLINDER

Here we present the computational results of the unsteady three-dimensional flows around a rectangular cylinder at rest and oscillating in a torsional mode.

Figure 2 illustrates instantaneous pressure contours around the cylinder at rest. It can be found that the flow is separated from the frontal corner of a rectangular cylinder and the shear layer is formed in the side wake. The separated shear layer is rolling up and evolving vortices. The larger vortices continuously hit on the side surface of the cylinder. The instantaneous pressure contours on the side surface of a cylinder are shown in Fig. 3. The low negative pressure in the windward region of the side surface is found to be almost constant. This negative pressure recovers suddenly close to the reattachment location of the separated shear layer. This tendency is in good agreement with the previous experimental data. The instantaneous pressure contours on the spanwise section along the grid line close to the separated shear layer(see Fig. 2) are also given in Fig. 4. The two-dimensional structures of the separated shear layer change into three-dimensional structures by the vortex instability. The time variation of pressure coefficients(C_P) is depicted in Fig. 5. On the windward side surface of the cylinder, the C_P values are almost constant in time and we can assume there exists a separation bubble stably. We can find the convective characteristics in the pressure fluctuations after the reattachment.

We present the computational results of the flow around an oscillating rectangular cylinder in a torsional mode at the reduced velocityVr=5.0 (U_0/f_mB, f_m: the frequency of forced oscillation). The angle θ of torsional forced-vibration is given as $\theta(t) = \theta_0 \sin(2\pi f_m t)$, where θ_0=5°(θ_0: the amplitude of torsional angle). At Vr=5.0, the resonant phenomena are observed in the previous 2-D computation[2]. Figure 6 illustrates the instantaneous pressure contours in the wake of the cylinder. We can see the cylinder oscillation completely controls the vortex-shedding whose frequency is coincident with the torsional frequency. The spanwise structures of pressure become two-dimensionalized by the motion of the cylinder(Fig. 7). It is expected that the two-dimensional simulation is effective for the aeroelastic problem.

5. AEROELASTIC BEHAVIOR OF BLUFF CYLINDERS

The 2-D computational case of the torsional free oscillation of a rectangular cylinder is provided. The mass-damping parameter(the Scruton number $Sc=2I/\rho D^4 \cdot 2\pi h$, h:structural damping) is equal to 0.483. For a initial condition, the torsional angle of 0.5° is imposed at first stage of computation.

The torsional amplitude of response is presented as a function of the reduced velocity in Fig. 8. We depict the computational response(h=0.01) due to the fluid forces obtained from the elastic model as well as the rigid model. The previous experimental data[6],[7] show that the torsional response becomes larger suddenly over Vr=5.0 (U_0/f_0B, f_0:the natural frequency of torsional mode) and the resonant phenomenon is observed approximately at Vr=5.0~8.0 for this

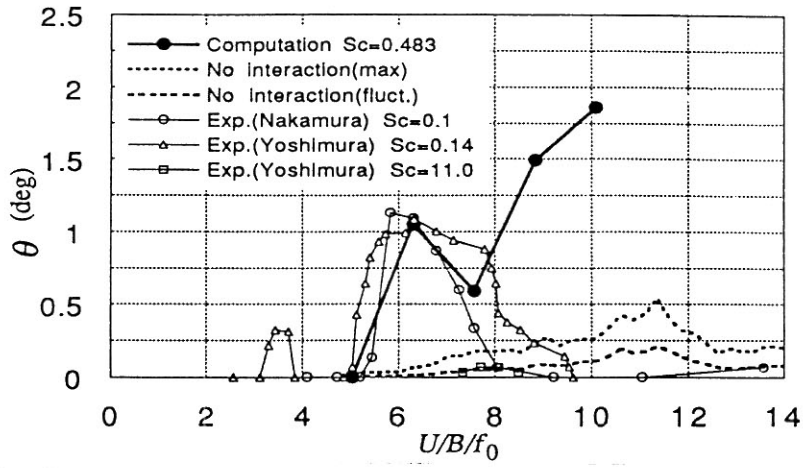


Fig. 8 Torsional amplitude versus reduced velocity for an elastically mounted rectangular cylinder (Re=10^4).

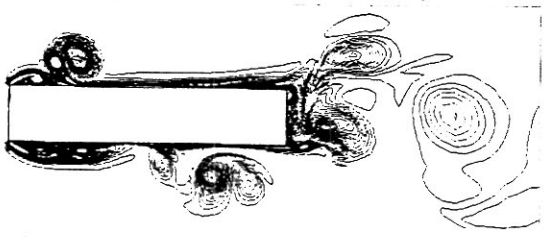


Fig. 9 Instantaneous vorticity contours around the freely-oscillating rectangular cylinder (Re=10^4).

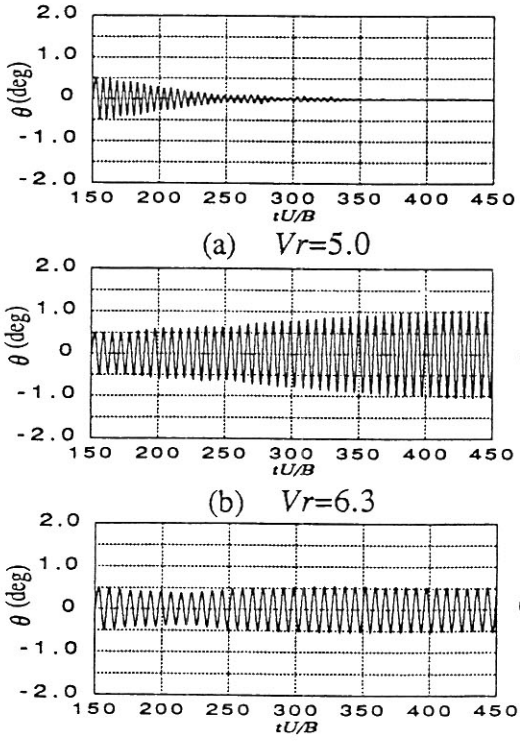


Fig. 10 Time histories of torsional response

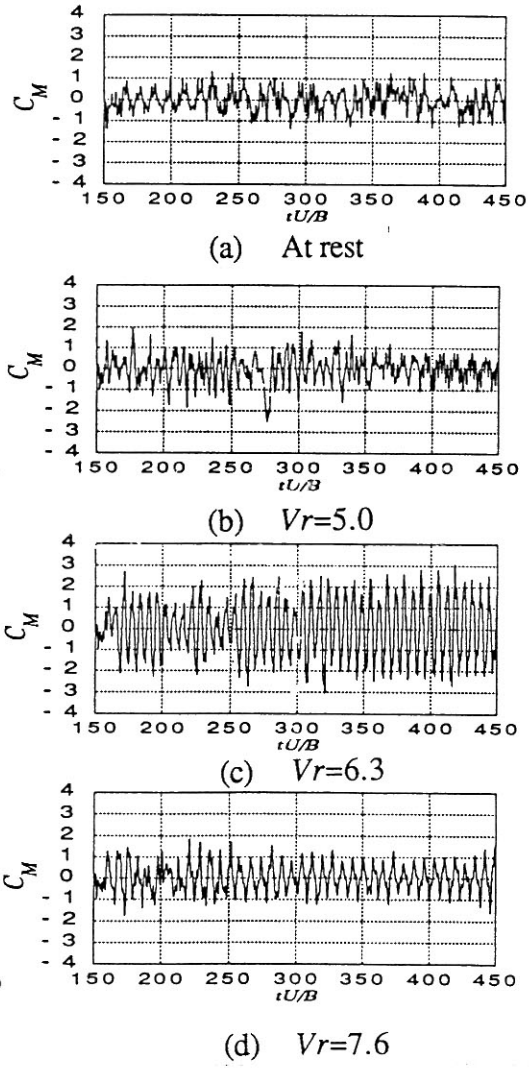


Fig. 11 Time histories of torque coefficients

parameter. The computational results are in agreement with the experimental data with regard to the occurrence condition of the vortex-induced vibrations or the peak response. In case where there is no interaction between the cylinder oscillation and the fluid force, the maximum response is given at higher Vr. Figure 9 illustrates the instantaneous vorticity contours around the cylinder at Vr=6.3. We can see the vortices shed from the frontal and the rear corner, depending on the motion of the cylinder. The time histories of the torsional response at Vr=5.0,6.3 and 7.6 are shown in Fig. 10. In case of Vr=5.0, the initial torsion is damped. However at Vr=6.3 the cylinder oscillates by the natural frequency and the amplitude is gradually increasing. Then it becomes the constant value and the response enters the limit cycle. The time histories of the torque coefficients(C_M) are given in Fig. 11, including the case of the rigid model. According to the rigid model, the dominant frequency is 0.085. In case of Vr=5.0, the dominant frequency agree with the natural frequency before damp but it becomes the same value as the rigid model after damp. On the other hand, at Vr=6.3 and 7.6, the C_M value is changing as a sinusoidal curve under the natural frequency. It means that the unsteady forces generated by the motion of the cylinder can be simulated.

5. CONCLUSION

We simulate the unsteady flow around an oscillating rectangular cylinder by means of the direct finite difference technique without any turbulence model. The pressure distribution on the spanwise surface of the oscillating cylinder is provided and the unsteady forces in case that the aeroelastic instabilities occur are investigated. Accordingly the mechanism of vortex-induced vibration is discussed in comparison with the experimental data.

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