A time-independent finite difference analysis of flow induced cylinder vibration

Bang-Fuh Chen[1]

Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan 804, Fax: 886-7-5255065, E-mail: chenbf@mail.nsysu.edu.tw

Chih-Chung Chu[2]

Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan 804

ABSTRACT

In marine engineering, offshore structures often encounter waves, currents and earthquake excitations. The fluid-structure interaction is a topic of primary interest in research and design. One of the basic studies is flow across a moving cylinder. During earthquake excitations, the relative velocity between the cross flow (current) and a moving cylinder (induced by ground motion) could be very large and the flow might be turbulent. The numerical simulations of viscous oscillating fluid flow pass a circular cylinder with a spring support are presented in this study. The cylinder of spring support is free to move in the stream-wise direction and damping ratio and spring stiffness is considered in this moving system, the Reynolds numbers of inflow is 200, and KC number is 4 for simulations cases. The numerical finite differences method and coordinates transformation system used to simulate these cases. There are 2 cases presented, one is harmonic oscillating flow pass a fixed cylinder, the other is harmonic oscillating flow pass a cylinder with spring support.

1. INTRODUCTION

Uniform steady flow passing a fixed cylinder was investigated for many decades, there are many data and results from theoretical analysis, numerical simulations and experimentally investigates. Such as Collins and Dennis (1973, Re = 5 to ∞), Ta Phuoc Loc (1980, Re = 300, 550 and 1,000; 1985 Re = 3,000 and 9,500), Braza (1986, Re = 100, 200 and 1000), Smith (1988, Re = 2,500~10^5). Karniadakis (1992, Re = 200~500). Koumoutsakos (1995, Re = 100 and 200). Persillon (1998, Re = 100~300). And then the relative research extend to adding the oscillating frequency, the input conditions of inflow was changed from stead flow to oscillating flow or changed from fixed cylinder to oscillating cylinder in static fluid, such as Justesen (1991, β = 196~1,035, KC = 0~26), Anagnostopoulos (1998, Re = 200, KC = 2~20), Dütsch (1998, Re=100 and KC = 5) and so on.

This study major simulated cylinder of free vibration in oscillating flow, involved damping ratio and spring stiffness in moving system. The Reynolds number is 200, and the KC number is 4. The oscillating frequency of flow is given a harmonic sine function U(t), the maximum velocity of oscillating flow is U_0. The sketch of simulation is show Fig-1.

$$U(t) = U_0 \times \sin(2 \times \pi \times f \times t) \quad \pi \tag{1}$$

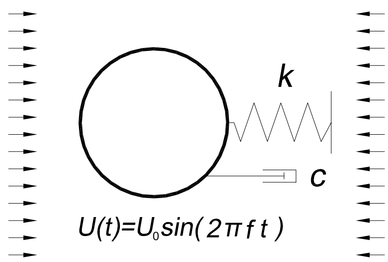


Fig-1

2. Numerical method

2.1 Coordinate transformation

Since the oscillating cylinder surface is varying with time, the first of the following equations is used to remove the dependence of b_2 on time (Hung 1981).

$$r^* = \frac{r' - a}{b_2(\phi, t) - a} \qquad (2)$$

$$R = \beta_1 + (r^* - \beta_1)e^{k_1 r^* (r^* - 1)} \qquad (3)$$

$$\Phi = \frac{\phi}{\pi} \qquad (4)$$

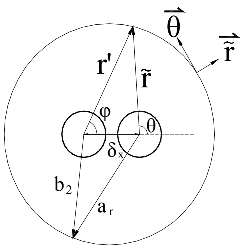


Fig-2 The definition of sketch of the problem

2.2 Governing equations

This study used the finite difference method to solve the stream function and vorticity transport equations. The coordinate system is attached on the circular cylinder like Fig-2, and the governing equations are as following equation (5) and (6):

$$\omega = -[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial \varphi}{\partial r}) + \frac{1}{r^2}\frac{\partial^2 \varphi}{\partial \theta^2} \qquad (5)$$

$$\frac{\partial \omega}{\partial t} + \frac{1}{r}\cdot(\frac{\partial \varphi}{\partial \theta}\cdot\frac{\partial \omega}{\partial r} - \frac{\partial \varphi}{\partial r}\frac{\partial \omega}{\partial \theta}) = \eta \cdot \nabla^2 \omega \qquad (6)$$

Also shown in the definition sketch, b_2 is the distance between outer boundary and the instant center of the moving circular cylinder and can be shown and expressed as

$$b_2(\phi, t) = -\delta_x(t)\cos\phi + \{a_r{}^2 - [\delta_x(t)\sin\phi]^2\}^{\frac{1}{2}} \qquad (7)$$

in which $\delta_x(t)$ is displacement of the oscillating cylinder and a_r is distance between the outer boundary and the fixed origin. The cylinder face is mapped onto r* = 0 and the outer boundary onto r* = 1. And the second transformation would map ϕ onto a region Φ = 0 and 2. Thus, the time-dependent boundary of the moving cylinder is transformed to a fixed computational domain of a rectangular region. Because of the transient boundary layer development, fine grids in the radial direction are required around the cylinder. The coordinates r* is further transformed so that the layer nears the cylinder will be stretched to produce finer grid meshes Δr^* near the cylinder face.

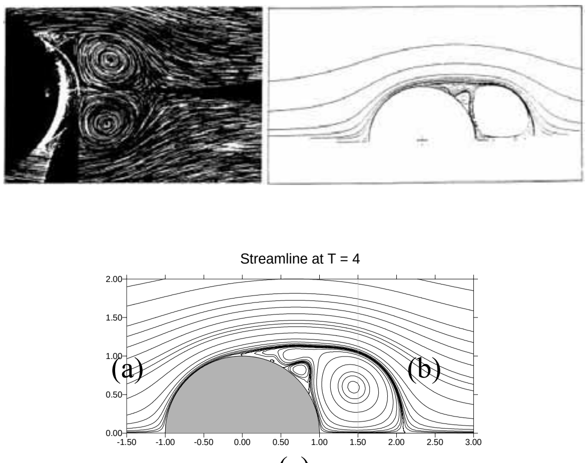
The numerical procedures are based on the Crank-Nicolson method. Since two equations are coupled, iteration is needed to achieve acceptable convergence condition. Secondly, calculate velocity fields and integrate the momentum equation to obtain the pressure on the cylinder surface. The flow around the cylinder is analyzed by relating the flow patterns with the acceleration and deceleration, the growth and decade of vortices, the pressure and shear around the moving cylinder. On the cylinder surface, the vorticity distribution and the moving of the separation point are correlated with the phases of oscillation, and with the pressure distributions on the cylinder. The flow patterns are solved by the developed finite difference method (Chen 1997), while the dynamic response of the cylinder oscillation is evaluated by direct Newmark integration method. The hydrodynamic force on the oscillating cylinder and the dynamic response of the cylinder motion are calculated and the forces are compared with that estimated from Morison's equation. The dependence of the dynamic response of the oscillating cylinder with Reynolds number and KC number is extensively studied and discussed. In order to gain the interaction relationship between cylinder and fluid, the one degree freedom vibration system involved here, the equation is (8), m is structure mass, c is damping coefficient, k is spring stiffness. The calculating procedures are as following steps: first, use the equation (1) and (2) combine coordinate transformation to get the vorticity values and then calculating force on cylinder surface, and from equation (8), use Newmark's method to get the displacement and velocity of next time step.

$$m\ddot{x} + c\dot{x} + kx = F(t) \qquad (8)$$

3. Results and discussion

3.1 Numerical validation

Ta Phuoc Loc (1985) presented the cross flow pass a fixed cylinder at Reynolds numbers equal 3000 by numerical simulation and made comparisons with the previous experimental results of Bouard and Coutanceau (1980). The experimental visualizations of Bouard and Coutanceau (1980) when T=4, Re=3000, is showed in Fig-3 (a). The streamline pattern of Ta Phuoc Loc (1985) at T = 4.0 is showed Fig-3 (b). The streamline pattern of present numerical simulation, is plotted in Fig-3 (c), and the comparison shows good agreement. Table 1 demonstrates a further detail comparison of wake height and length among three results. The numerical accuracy of present simulation is very good.



(c)

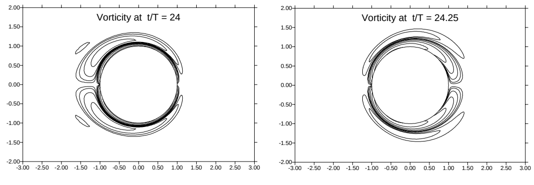
Fig-3 Streamline pattern of cross flow pass a fixed cylinder Re = 3000 at T = 4.0 (a) Bouard and Coutanceau (1980), (b) Ta Phuoc Loc (1985), (c) this study.

Table-1

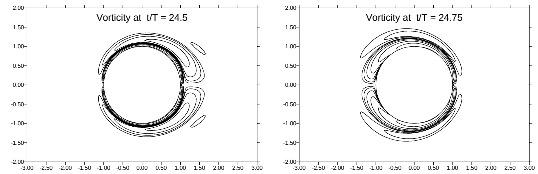
Comparison items for Re=3000, T=4	main wake length / radius	main wake height / radius
Bouard and Coutanceau (1980)	1.181	1.101
Ta Phuoc Loc (1985)	1.079	1.066
This study	1.109	1.118

3.2 Oscillating flow pass a fixed cylinder, Re=200, KC=4

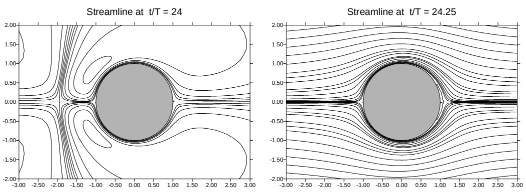
The case studied in this paper belongs to the range A of eight different flow patterns reported by Tatsuno and Bearman（1990）and there is no flow separation in this case.



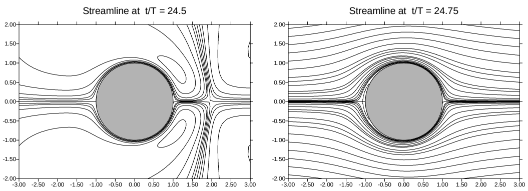
T = 24 T = 24.25



T = 24.5 T = 24.75



T = 24 T = 24.25



T = 24.5 T = 24.75

Fig. 4 The vorticity contour and streamline patterns development around cylinder.

The Fig-4, Fig-5, Fig-6 and Fig-7 show the vorticity contour and streamline patterns around cylinder at the T = 24, 24.25, 24.5 and 24.75 cycles. When oscillating flow pass the fixed cylinder on t/T = 24 cycle, the direction of flow just from toward west change to toward east, and the velocity of flow is zero at that time. When t/T = 24.25, the velocity of flow become maximum, and then decreasing to zero when t/T = 24.5.

Fig. 5 shows the in-line force history for oscillating flow pass a fixed cylinder for Re = 200, KC = 4.

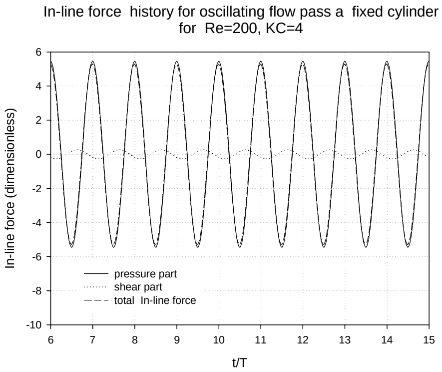


Fig. 5 The in line force acting on a fixed cylinder, Re = 200, KC = 4

3.3 Oscillating flow pass a cylinder with spring support, Re = 200, KC = 4

This case investigated two dimensional viscous flow patterns and the in-line response of a flexible cylinder in an oscillating flow for Re=200, KC=4. In equation (8), m is mass of unit length of cylinder, and m is 0.01 kg per unit length, k is spring stiffness, c is the damping coefficient. And the damping ratio ζ is equal to 0.05, about frequency ratio f_r is setup equal to 0.3. In equation (9), f_f is the frequency of oscillating flow, f_n is the natural frequency of the cylinder in air, and T_f is period of oscillating flow.

$$f_r = f_f / f_n = \frac{1/T_f}{\omega_n / 2\pi} = \frac{2\pi}{T_f \sqrt{k/m}} \qquad (9)$$

$$\zeta = c / 2m\omega_n \qquad (10)$$

$$k = \frac{4\pi^2 m}{T_f^{\ 2} f_r^{\ 2}} \qquad (11)$$

About the dynamic response system solution, P. Anagnostopoulos (1998) used the 4 order Runge-Kutta scheme. We use Newmark's method to solve for the displacement, velocity and acceleration of cylinder for next time step.

In a preliminary simulation results, Fig. 6 shows the in-line force acting on cylinder and the dynamic displacement of cylinder. As plotted in the figure, a mild phase lag exists between cylinder displacement and in-line force. Since the dynamic response of cylinder displacement and acceleration are in the same phase, we can find the lag between in-line force and dynamic acceleration and the viscous effect might affect or retard the momentum force generated by oscillating cylinder.

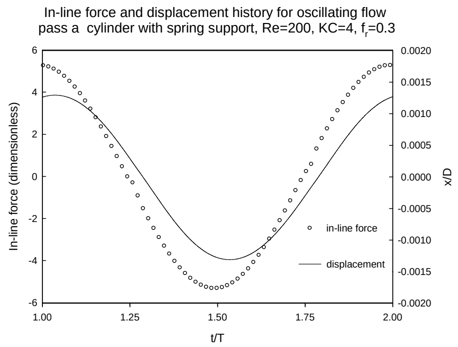


Fig. 6 The in line force acting on a spring attached cylinder, Re = 200, KC = 4

4. Conclusions

The numerical validation clearly shows the high accuracy of the present numerical model. The preliminary simulation results demonstrate the significant interaction of viscous and inertia effects on dynamic response of cylinder and forces acting on the cylinder and more detailed investigation should be made to obtain more response characteristics.

4. REFERENCES

Anagnostopoulos, P. and Iliadis, G. 1998 Numerical study of the flow pattern and the in-line response of a flexible cylinder in an oscillating stream. Journal of Fluids and Structures. 12, 225-258.

Braza, M., Chassaing, P. and Ha Minh, H. 1986 Numerical study and physical analysis of the pressure and velocity fields in the near wake of a circular cylinder. J. Fluid Mech., 165, 79-130.

Dütsch, H., Durst, F., Becker, S. and Linenhart, H. 1998 Low-Reynolds-number flow around an oscillating circular cylinder at low Keulegan-Carpenter numbers. J. Fluid Mech. 360, 249-271.

Justesen, P. 1991 A numerical study of oscillating flow around a circular cylinder. J. Fluid Mech. 222, 157-196.

Karanth, D. Rankin, G. W. and Sridhar, K. 1995 Computational study of flow past a cylinder with combine in-line and transverse oscillation. Computational Mechanics. 16, 1-10.

Koumoutsakos, P. and Leonard, A. 1995 High-resolution simulations of the flow around an impulsively started cylinder using vortex methods. J. Fluid Mech., 296, 1-38.

Persillon, H, and Braza, M. 1998 Physical analysis of the transition to turbulence in the wake of a circular cylinder by three-dimensional Navier-Stokes simulation. J. Fluid Mech., 365, 23-88.

Ta Phuoc Loc. 1980 Numerical analysis of unsteady secondary vortices generated by an impulsively started circular cylinder. J. Fluid Mech., 100, 111-128.

Ta Phuoc Loc and Bouard, R. 1985 Numerical solution of the early stage of the unsteady viscous flow around a circular cylinder: a comparison with experimental visualization and measurements. J. Fluid Mech., 160, 93-117.