STUDY ON THE FLOW PAST CIRCULAR CYLINDER WITH OSCILLATING ROTATION BY LES

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ABSTRACT

Flow past circular cylinder with oscillating rotation is investigated by Large Eddy Simulation (LES) at Reynolds number 3900 based on the free stream velocity *U* and radius of the cylinder *D*. The dynamic Smagorinsky model is used for the closure of the subgrid stress and the immersed boundary method is applied to the non-slip condition at cylinder surface. The results of stationary cylinder are compared with previous numerical and experimental data with satisfaction. The drug is increased when the oscillation rate is equal to the vortex shedding frequency of the flow past stationary cylinder while the drug is reduced at the oscillating rate equaling five times of vortex shedding frequency of the flow past stationary cylinder. The vortex patterns show that the big vortices after the cylinder are suppressed at the high oscillation frequency and thus the drug is reduced.

INTRODUCTION

Flow past circular cylinder is an interesting case which involves most of important phenomena in complex flows, such as flow transition, separation, vortex shedding and so on. In this paper the flow past circular cylinder with rotation is investigated by Large Eddy Simulation at subcritical Reynolds number.

Large Eddy Simulation (LES) is a promising method for complex turbulent flows, in particular for non-stationary turbulent flows. The dynamic Smagrorinsky model is used for the closure of subgrid stress in LES. The governing equations are solved numerically by the finite-volume method and SIMPLE algorithm is used for handling the pressure-velocity coupling. The immersed boundary method [1] is utilized for the boundary condition at the cylinder surface in order to use simple rectangular grid mesh. The Reynolds number, defined as *UD/ν*, is fixed at 3900. Two oscillating rates are tested with non-dimensional frequency *f*=0.2 and *f*=1.0 respectively. The results of stationary cylinder are compared with previous numerical and experimental data with satisfaction. The drug is increased when the oscillation frequency is equal to the vortex shedding frequency of the flow past stationary cylinder while the drug is reduced at oscillating rate equaling five times of vortex shedding frequency of the flow past stationary cylinder. The vortex patterns show that the big vortices after the cylinder are suppressed at the high oscillation frequency and thus the drug is reduced.

NUMERICAL METHODS

The governing equation of LES can be written as

$$\frac{\partial \bar{u}_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\bar{u}_i\bar{u}_j\right)=-\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left\{\nu\left(\frac{\partial \bar{u}_i}{\partial x_j}+\frac{\partial \bar{u}_j}{\partial x_i}\right)+\tau_{ij}\right\} \qquad (1)$$

$$\frac{\partial \bar{u}_i}{\partial x_i}=0 \qquad (2)$$

in which the upper bar on the flow variables stands for the filtered quantity and $\tau_{ij} = \bar{u}_i\bar{u}_j - \overline{u_i u_j}$ stands for the subgrid stress which is closed by dynamic Smagorinsky model that

$$\tau_{ij} = 2\nu_t\left(\frac{\partial \bar{u}_i}{\partial x_j}+\frac{\partial \bar{u}_j}{\partial x_i}\right)+\frac{1}{3}\tau_{kk}\delta_{ij} \qquad (3)$$

where $\nu_t = C\Delta^2\left(2S_{ij}S_{ij}\right)^{1/2}$ and the coefficient C is determined by a dynamic procedure. proposed by Lilly (1992) [2].

The LES equation is solved numerically by Finite Volume Method (FVM) with QUICK scheme for the convective term and second order central finite differentiation for the diffusion term. The non-staggered rectangular grids are used in combination with immersed boundary method (IBM). To avoid the decoupling between velocity and pressure the momentum interpolation with third order accuracy is utilized. The immersed boundary method is effective for complex geometry of flow boundary as well as in numerical computation on rectangular grids. It is necessary to insert boundary force in order to satisfy non-slip condition at the solid wall. A number of methods are proposed to impose the boundary force [3]. We use direct forcing method in the time advancement such that

$$\bar{u}^{n+1} - \bar{u}^{n} = \Delta t\left(RHS + f\right) \qquad (4)$$

$$f = -RHS + \frac{V_b - \bar{u}^n}{\Delta t} \qquad (5)$$

in the above equations f is the boundary force, *RHS* stands for the right hand terms of LES equation and V_b is the velocity of the solid boundary. A relatively large time step can be accepted in time integration in use of the direct forcing method. The second order accuracy is applied in numerical integration of time advancement that

$$\frac{\partial \phi}{\partial t} = \frac{3\phi^{n+1} - 4\phi^{n} + \phi^{n-1}}{2\Delta t} \qquad (6)$$

The boundary conditions are posed as follows. The non-slip condition in the cylinder surface is satisfied by IBM and periodic condition is posed in spanwise direction , i.e. the axial direction of the cylinder. The free stream velocity is imposed at the inlet boundary and non-reflection condition at the outlet. At upper and lower boundaries symmetrical condition is employed

$$\frac{\partial u}{\partial y} = \frac{\partial w}{\partial y} = 0 \quad \text{and } v=0 \qquad (7)$$

in which x, y stands for the horizontal (streamwise) and vertical directions on the plane perpendicular to the cylinder axis and z for spanwise direction. The computational domain is designed in a box with $71d$, $36d$ and $\pi d/2$ in the horizontal, vertical and spanwise directions respectively. The grid points are given as 400×200×20 in x, y, z directions. The center of the cylinder is located in $10d$ behind the inlet boundary. The non-dimensional time step is 0.01.

Table 1. Results of flow past stationary circular cylinder

	θ_s	L_b	C_d	St number
Present	89^0	1.32	1.09	0.19
Exp.	$86^0 \pm 2$	1.4 ± 0.1	0.99 ± 0.05	0.215 ± 0.005
Num.	88^0	1.35	1.04	0.21

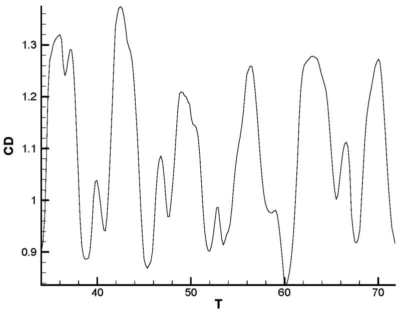
RESULTS

The dynamic performance for the flow past stationary cylinder is given in Table 1 and the results show good agreement with previous experimental and cimputational data.

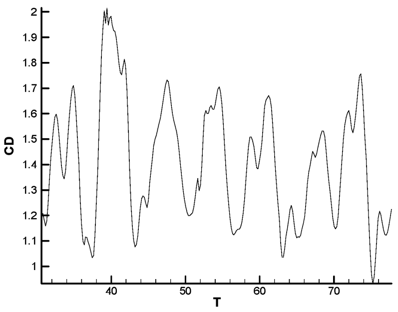
The present numerical results of flow past cylinder with oscillating rotation show that the drag is increased at the non-dimensional frequency of 0.2, equaling the frequency of vortex shedding of flow past stationary cylinder while the drag force is reduced at the non-dimensional frequency of 1.0.

The time series of drag are compared between stationary and oscillating cylinders as shown in Figure 1. The peak frequency is around 0.2 for both stationary and oscillating cylinders. The higher peak value of drag is produced at f=0.2; as a result the mean drag is increased by 29.3%. At higher oscillating frequency the mean drag is decreased by 6%.

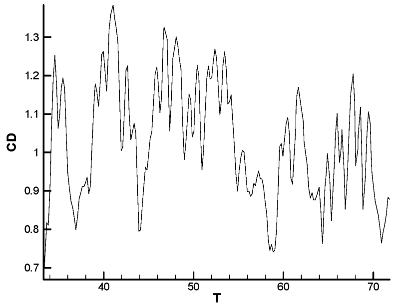
The increasing or decreasing of drag in oscillating rotation cases can be interpreted by the vortex patterns in the wake of the flows. Figure 2 shows that the vortex patterns are similar between flow past stationary cylinder and rotating cylinder with f=0.2, nonetheless the vortex shedding is more concentrated in the oscillating case due to the phase locking and this is the reason for higher mean drag. On contrast, the small vortices is shedding at higher frequency f=1.0 and the big vortex is suppressed, hence the mean drag is reduced.



(a) Stationary

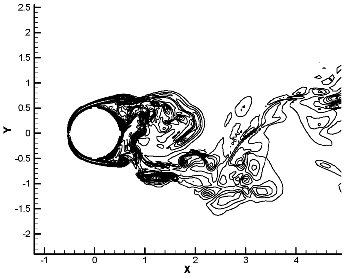


(b) *f*=0.2

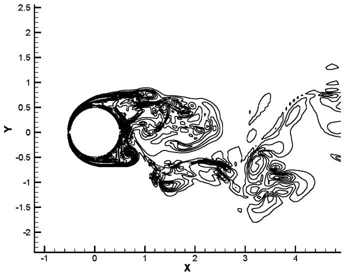


(c) *f*=1.0

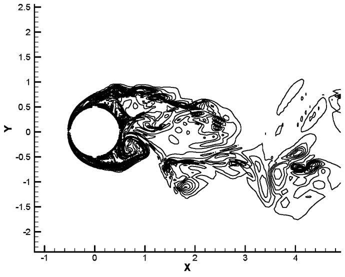
Figure 1 Comparison of time series of drag among flows around stationary cylinder and with oscillating rotation



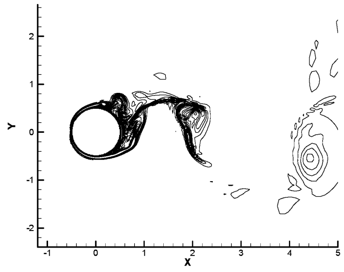
(a) stationary cylinder, *t*=54.9



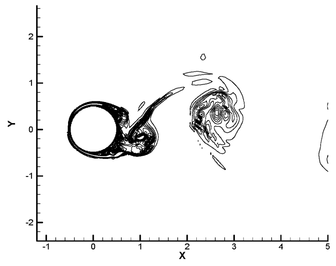
(b) stationary cylinder, *t*=55.8



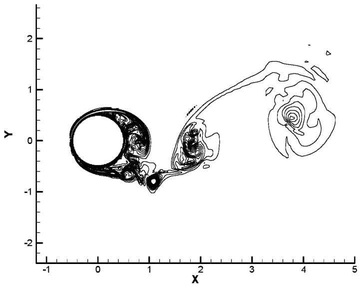
(c) stationary cylinder, *t*=56.7



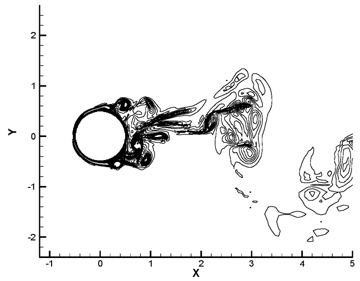
(d) *f*=0.2, *t*=45



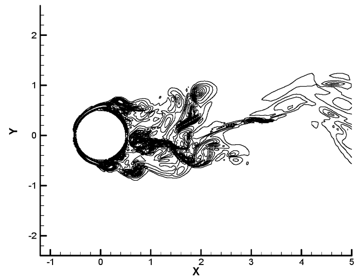
(d) *f*=0.2, *t*=45



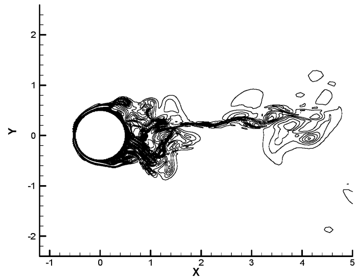
(f) *f*=0.2, *t*=45



(g) *f*=1.0, *t*=52.2



(h) *f*=1.0, *t*=54



(i) *f*=1.0, *t*=55.8

Figure 2 Comparison of vortex patterns among flows around stationary and oscillating cylinders

CONCLUDING REMARKS

1. The dynamic performance of flows past cylinder with oscillating rotation can be predicted by LES with dynamic Smagrorinsky model.
2. The mean drag is increased when the oscillating frequency equals the vortex shedding frequency of flow past stationary cylinder due to phase lock.
3. The oscillating rotation with higher frequency suppresses the bigger vortices and reduces the mean drag.
4. The drag performance is closely related to the mechanism of vortex shedding.

ACKNOWLEGEMENT

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