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Numerical study of flow over a circular cylinder in oscillatory flows with zero-mean and non-zero-mean velocities

Shuyang Cao [a,*], Ming Li [b]

[a] State Key Lab for Disaster Reduction in Civil Engineering, Tongji University, Siping Road 1239, Shanghai 200092, China
[b] Wuhan Bridge Science Research Institute, Wuhan, China

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ABSTRACT

This paper numerically investigates flow over a circular cylinder in oscillatory flows with zero-mean and non-zero-mean velocities. The effects of Keulegan–Carpenter number and amplitude ratio number on vortex shedding around a cylinder are investigated. The applicability of Morrison's equation to prediction of the time histories of drag and lift forces is discussed. Results of the present study show that the unsteady flow pattern around a circular cylinder depends strongly on both Keulegan–Carpenter number and amplitude ratio number, in addition to Reynolds number. Although the time history of drag force can be acceptably approximated by Morrison's equation in both zero-mean and non-zero-mean velocity flows, multiple vortex shedding frequencies need to be included if Morrison's equation is extended to approximate the time history of lift force.

1. Introduction

Vortex shedding behind two-dimensional circular cylinders has been one of the most studied subjects in fields associated with fluid–structure interaction in the past several decades because of its practical and theoretical importance. Although a quite comprehensive understanding of vortex dynamics in a cylinder's wake has been achieved, the simplicity of the geometry and the abundance of interesting flow features continue to make this phenomenon the subject of many current studies. Unlike the uniform smooth or fully-developed turbulent oncoming flow conditions considered in many previous studies, this paper studies unsteady flow past a circular cylinder placed in a sinusoidal oscillatory flow, whose time-dependent velocity $U(t)$ is expressed as

$$U(t) = U_0 + U_m \sin \omega t \tag{1}$$

where ω is the angular frequency ($\omega = 2\pi/T$, where T is the period of oscillation), U_0 is the mean velocity and U_m is the amplitude of sinusoidal velocity fluctuation. The combination of the variables of U_0, U_m, and T determines the flow pattern of oncoming flow and accordingly the aerodynamic forces acting on the circular cylinder placed in it. In addition to the Reynolds number, there are two important dimensionless parameters that determine the unsteady flow around a circular cylinder, i.e. Keulegan–Carpenter number (referred as KC number later) and amplitude ratio number (referred as AR number later). KC number ($\mathrm{KC} = U_m T/D$) is the ratio of the distance the flow can move in time T with velocity U_m to the diameter D of the circular cylinder, while AR number ($\mathrm{AR} = U_m/U_0$) is the ratio of the amplitude of sinusoidal velocity fluctuation U_m to the mean velocity U_0. This study considers sinusoidal oscillatory flows with zero-mean ($U_0 = 0$) and non-zero mean ($U_0 \neq 0$) velocities. When $U_0 = 0$, the free stream flow oscillates relative to the circular cylinder. When $U_0 \neq 0$, the amplitude and direction of the velocity varies in time. The flow is unidirectional when $\mathrm{AR} < 1.0$ but becomes bidirectional when $\mathrm{AR} > 1.0$. Considering that wind velocity is usually unidirectional, the present study considers only the unidirectional sinusoidal flow cases for the non-zero-mean velocity situation. The flow around a circular cylinder in oscillating flows is chosen as the study subject of the present study because it may be considered as a starting point to study turbulence effects on bluff body aerodynamics, in addition to its direct applicability to ocean engineering problems. In mathematics, the time-dependent velocity fluctuation of turbulence can be decomposed into a set of simple oscillating functions. Although an oscillatory flow contains one frequency component of velocity fluctuation only, it may shed light on the effects of turbulence intensity by providing knowledge of the effects of AR number, and the effects of turbulence scale by providing knowledge of KC number.

The majority of the past studies on the effects of KC number on flow over a circular cylinder were conducted for the zero-mean velocity oscillatory flow situation, and the study interests were mainly the flow structure and empirical equations to estimate the in-line force on a circular cylinder. Morison et al. (1950) proposed a semi-empirical equation to estimate the force on a circular cylinder

* Corresponding author.
E-mail address: shuyang@tongji.edu.cn (S. Cao).

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subjected to zero-mean velocity sinusoidal oscillatory flow. Morison's work was followed by many researchers (Keulegan and Carpenter, 1958; Williamson, 1985; Sarpkaya, 1986; Tatsuno and Bearman, 1990; Okajima et al., 1997), who investigated the applicability of Morison's equation while studying the dependence of the flow structure on KC number and Reynolds number. For instance, Tatsuno and Bearman (1990) categorized eight vortex shedding modes, such as transverse street, single pair, double pair and so on, in an oscillatory flow. However, the discussion on Morison's equation was limited to the in-line drag force in the majority of the past studies. Compared with zero-mean velocity oscillatory flow, there have been fewer studies on non-zero-mean velocity oscillatory flow. A few researchers studied whether Morison's equation is applicable to sinusoidal oscillatory flow with a non-zero-mean velocity (Nomura et al., 2003; Chen et al., 2009; An et al., 2011). Meanwhile, Nomura et al. (2003) proposed to extend Morison's equation to predict lift force in an oscillatory flow.

In this study, three-dimensional unsteady Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) are performed to study the flow around a circular cylinder subjected to sinusoidal oscillatory flow with zero-mean and non-zero-mean velocities. The effects of KC number and AR number are mainly discussed while the effects of Reynolds number are also noted. For zero-mean velocity flow, two KC numbers, KC=10 with Re=200 and KC=17 with Re=1615, are considered to illustrate the effects of KC number. Reynolds number is defined as $Re = U_m \times D/\nu$, where ν is the kinematic viscosity. For non-zero-mean velocity flow, three AR numbers, AR=0.2, 0.5, and 1.0 while fixing the KC number at KC=10, are considered at Re=200 and 1615, respectively, in order to study the effects of AR number. Reynolds number here is defined as $Re = (U_0 + U_m) \times D/\nu$. The main reason for studying at two Reynolds numbers is as follows. Although the coherent vortex structure in the spanwise direction starts to appear from about Re=185 (Mode A), the vortex shedding is close to two-dimensional and there is less randomness in the time history of drag force at Re=200. However, the amplitude of the time history of drag force is no longer constant because the vortex shedding is completely three-dimensional at Re=1615. The present simulation involves the estimation of the time histories of drag and lift forces by Morrison's equation, so it is better to conduct the study at different levels of randomness in the time histories. In this study, the parameters related to vortex shedding such as Strouhal number and drag and lift coefficients, and their dependence on KC number and AR number, are presented. The instantaneous flow structure at different KC and AR numbers are illustrated in order to improve understanding of wake structure and the force acting on the cylinder. The applicability of Morison's equation to estimating the time histories of the drag and lift forces in zero-mean and non-zero-mean velocity oscillating flows is also investigated.

2. Numerical method

2.1. Governing equations and numerical procedure

The governing equations for Direct Numerical Simulation (Re=200) and Large Eddy Simulation (Re=1615) are the non-filtered and filtered continuity equation and Navier–Stokes equations. Eqs. (2) and (3) are the governing equations for LES.

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

$$\frac{\partial(\bar{u}_i)}{\partial t} + \frac{\partial(\bar{u}_i\bar{u}_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \nu\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{3}$$

where u_i (i=1, 2, 3) are the three velocity components and p, t, and ν denote pressure, time, and kinematic viscosity, respectively. The over-bar denotes the space filtered quantities. In LES, the grid-scale turbulence is solved while the sub-grid-scale turbulence is modeled. The subgrid scale stresses (SGS stress), $\tau_{ij} = \overline{u_i u_j} - \bar{u}_i\bar{u}_j$, are expressed in Eq. (4),

$$\tau_{ij} - \frac{1}{3}\delta_{ij}\tau_{kk} = -2\nu_{SGS}\bar{S}_{ij} = \nu_{SGS}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) \tag{4}$$

where $\bar{S}_{ij}$ is the strain rate tensor, ν_{SGS} is the SGS eddy viscosity and

$$\nu_{SGS} = (C_S\bar{\Delta})^2\left|\bar{S}\right| \tag{5}$$

where C_S is the Smagorinsky constant, which changes depending on the type of flow. In the present study, the value of the Smagorinsky constant is C_s=0.1, which is often adopted by numerical simulations of the flow over bluff bodies (Rodi, 1997). The size of the grid filter is $\bar{\Delta} = (\Delta x \Delta y \Delta z)^{1/3}$. For Direct Numerical Simulation at Re=200, there is no filter operation, and the last term on the right hand side of Eq. (3) is absent.

Time-dependent unsteady finite volume approximation of the incompressible Navier–Stokes equations is performed. An open source solver OpenFOAM is utilized to solve the governing equations of fluids, but the options offered by OpenFOAM for simulation are carefully selected in order to achieve reliable results. In the simulation, a second-order central difference scheme is used for the convection terms and the diffusion terms. An implicit second-order time-advancing scheme is chosen for temporal discretization to obtain stable and accurate simulation. In addition, a PSIO algorithm is utilized to enhance the coupling of pressure and velocity in the numerical procedure. In addition, the convergence criterion of the iterative calculation is set to 1.0×10^{-6}, which requires about 40 iterations to satisfy in the simulation.

2.2. Calculation domain

Table 1 summarizes the information related to the grid system and the computational domain. The computational domain is comprised of two regions. An O-type grid system with a circular cylinder placed in the center is set to the inner region surrounded by four arcs whose radius equal $2.5\sqrt{2}D$ while an H-type grid is given to the remaining outer region. The depth of the first grid near the body surface is given empirically as $0.1\sqrt{Re}$ to adequately resolve the flow. For more efficient simulations, the inner computational domain is spatially resolved such that a dense clustering of grid points is applied near the cylinder while a coarser grid is used away from the cylinder. Considering the difference between the spanwise vortex structures for Re=200 and Re=1615, the length of the computational domain in the spanwise direction is 7D and 3.2D, respectively for Re=200 at Re=1615, which is considered sufficiently larger than the dominant wavelength $\lambda_Z \cdot \left(\lambda_Z/D \sim 25/\sqrt{\mathrm{Re}}\right)$ of longitudinal vortex in the spanwise direction (Williamson et al., 1995).

Table 1
Grid information.

Re	Domain size	Total grids	Spanwise grid no.	Central region: Radial grid No.	Central region: Radial grid First grid	Central region: Cir. grid no.
200	$40D \times 20D \times 7D$	575,040	24	90	0.006D	112
1615	$40D \times 20D \times 3.2D$	1,103,520	30	116	0.0025D	160