Ocean Engineering 146 (2017) 324–338

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Locked-on vortex shedding modes from a rotationally oscillating circular cylinder

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ARTICLE INFO

Keywords:
Navier-Stokes equations
HOC
Oscillations
Rotation
Vortex shedding
Lock-on

ABSTRACT

Numerical simulations of unsteady two-dimensional flow around a rotationally oscillating circular cylinder, placed in a uniform cross flow of a constant property Newtonian fluid, are performed at a fixed Reynolds number of 200. The investigation is based on the solutions of stream function-vorticity formulation of Navier-Stokes equations on non-uniform polar grids using a higher order compact (HOC) formulation. The flow field is mainly influenced by Reynolds number, *Re*, maximum angular velocity of the cylinder, α_m, and the frequency ratio, f/f_0, which represents the ratio between the frequency of oscillation, f, and the natural vortex shedding frequency, f_0. The ranges considered for these parameters are $0.5 \leqslant \alpha_m \leqslant 6.0$ and $0.5 \leqslant f/f_0 \leqslant 3.0$. The resulting vortex formation modes and lock-on phenomena behind the cylinder as well as the fluid forces acting on the cylinder are analyzed. Occurrence of new multiple lock-on regions is demonstrated in detail by the variation of f and α_m. The instances of high drag reduction at high values of α_m are confirmed. Comparisons with previous numerical and experimental results verify the accuracy and validity of the present study.

1. Introduction

The investigation of flow around oscillating bluff bodies has been a primary task in the design of numerous cylindrical structures. The key feature of interest for flow around oscillating bodies is the periodic vortex shedding phenomenon and how it can lead to better understanding of structure failures. Hence, due to practical significance of this type of flow, numerous fundamental, experimental, analytical and numerical studies have been performed over the years; see, for example, the recent works of Sarpkaya (2004), Bearman and Obasaju (1982), Bearman (2011), Ray (2011), Williamson and Govardhan (2004), Sumer and Fredsøe (1997), Baranyi (2008), Poncet (2002), Koide et al. (2002), Mittal and Ray (2013, 2015), Mittal et al. (2016), Mittal (2016) and Al-Mdallal (Al-Mdallal, 2015; Al-Mdallal and Mahfouz, 2017).

Rotational oscillation of the cylinder in the presence of uniform stream has been found to provide an important means of flow control. Such studies throw light on mechanisms that reduce forces or suppress vortex shedding. In an early numerical simulation by Okajima et al. (1975), it was reported that no periodic wake is found behind a stationary cylinder for $Re = 40$, but for the same Re and $f = 0.11$, forced periodic oscillation triggers a periodic wake in the near flow. Experiments performed by Taneda (1978) exhibit that vortex shedding could be nearly eliminated at very high oscillation frequencies. In their experimental study, Tokumaru and Dimotakis (1991) achieved a significant reduction in the drag (80%) for high Reynolds number $Re = 15000$. Lu and Sato (1996) numerically investigated the vortex shedding behavior at $Re = 200, 1000$ and 3000 and reported that the large-scale vortex structures in the near wake are nearly the same at these Reynolds numbers. Shiels and Leonard (2001) numerically studied the influence of rotational control on drag reduction for a range of Reynolds number from 150 to 15,000 and confirmed the findings of Tokumaru and Dimotakis (1991). Choi et al. (2002) reported that $Re = 1000$ can reduce the drag (about 60%) much more than the case of $Re = 100$ (about 12%). Concerning the vortex shedding phenomenon, several numerical studies have been conducted such as those by Baek and Sung (1998, 2000) who studied "lock-on" and "non lock-on" states with an extension to primary, secondary and tertiary lock-on states of lift coefficients. Chang et al (Cheng et al., 2001) applied hybrid vortex method (Cheng et al., 1995) to investigate the influence of oscillation parameters in the "lock-on" and "non-lock on" regimes on the wake structures, pressure distributions and other forces on the cylinder at $Re = 1000$. In addition, the flow behind an oscillating cylinder has been a model of flow for control and optimization (see He et al. (2000), Srinivas and Fujiswa (Srinivas and Fujisawa (2003), Haji and Janajrich (Janareh and Haji, 2008), Al-Mdallal (Al-Mdallal and

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https://doi.org/10.1016/j.oceaneng.2017.09.034
Received 14 May 2017; Received in revised form 22 August 2017; Accepted 24 September 2017

Nomenclature

R_0	radius of the circular cylinder
R_∞	radius of the circular far-field boundary
U_∞	free stream velocity
$\tilde{\alpha}$	dimensional oscillatory velocity
α	dimensionless oscillatory velocity ($= R_0\tilde{\alpha}/U_\infty$)
$\tilde{\alpha}_m$	dimensional maximum angular velocity
α_m	dimensionless maximum angular velocity ($= R_0\tilde{\alpha}_m/U_\infty$)
$\tilde{f}$	dimensional oscillation frequency
f	dimensionless oscillation frequency ($= R_0\tilde{f}/U_\infty$)
f_0	natural frequency of vortex shedding
τ	dimensional time
t	dimensionless time ($= \tau U_\infty/R_0$)
Re	Reynolds number($= 2R_0U_\infty/\nu$)
T	oscillation period of the cylinder
ν	kinematic viscosity of the fluid
C_L	lift coefficient
C_D	drag coefficient
r, θ	Polar coordinates
$\tilde{\psi}$, ψ	dimensional and dimensionless stream functions
$\tilde{\omega}$, ω	dimensional and dimensionless vorticities
$\tilde{u}$, u	dimensional and dimensionless radial velocities
$\tilde{v}$, v	dimensional and dimensionless tangential velocities

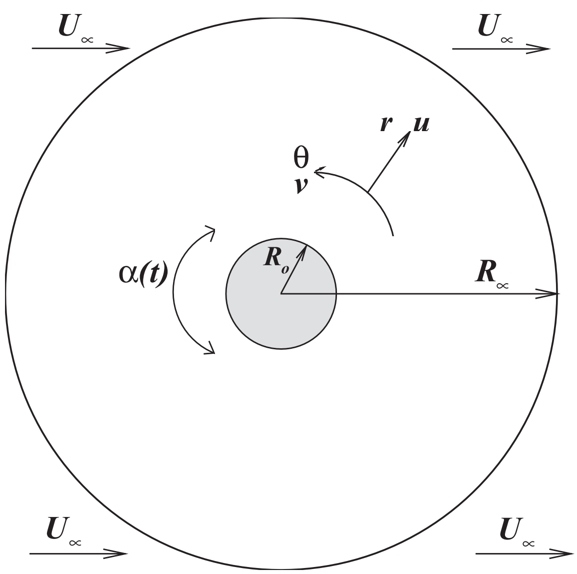

Fig. 1. The physical model and coordinate system of the flow domain.

Kocabiyik (2006), Al-Mdallal (2012), Lee and Lee (2006, 2008), Lu et al. (2011, 2016), Kumar (2016), Mahfouz and Badr (2000a, 2000b), and Sellappan and Pottebaum (2014), Baranyi (2009)).

The main objective of this paper is to numerically investigate the development of the near wake structure behind the circular cylinder undergoing rotational oscillations about its axis in the presence of a uniform stream of a viscous, incompressible fluid. Self-excited oscillations are exhibited by the flow with no external forcings, i.e. Ka′rma′n vortices are shed downstream. However, with an external forcing, vortex shedding is entrained with the motion of the cylinder. Hence, the vortex shedding frequency changes to match with the forced frequency of the cylinder. This phenomenon is termed as “lock-on”, when the self-excited oscillation synchronizes with the forced frequency of the cylinder provided the two frequencies are close (the primary lock-on). If the two frequencies are not close enough, a quasi-periodic or chaotic oscillation may occur. It has been observed that the entrainment still occurs when the frequency ratio, f/f_0, is in the neighbourhood of an integer or a fraction. Such an entrainment is termed as “super-harmonic” or “sub-harmonic” lock-on respectively. These frequency-lock-on regions are determined using the near-wake vorticity contours, power spectra of unsteady lift coefficient and phase diagrams (velocity end-point diagram in $u-v$ plane) at one point in the near wake. The modes of vortex shedding in the lock-on regions are presented and classified at a fixed value of Reynolds number $Re = 200$ and maximum angular velocity $\alpha_m \in [0.5, 6.0]$. The ratio of forced oscillation frequency, f, to Ka′rma′n vortex shedding frequency, f_0 is chosen from $f/f_0 = 0.5$ to 3, to classify the regions of fundamental, sub-harmonic and super-harmonic synchronization. The variation of forces acting on the cylinder as a function of forced oscillation frequency and maximum angular velocity is studied in detail.

In this paper, vortex shedding modes are referred according to the number of vortices shed from each side of the cylinder over the vortex shedding cycles in a lock-on period, $T_l = nT$, where n is either a fraction or an integer number. Here, T is the oscillation period of the cylinder and T_l is defined as the period of lock-on. For example, **2S** mode per T_l means that alternate counter-rotating single vortex is fed into the downstream wake from each side of the cylinder over T_l. It should be noted that the designation **2S** per T_l, when $T_l = T$ refers to the classical Ka′rma′n vortex street. However, the mode **P** + **S** per T_l mode means that two vortices are shed from one side of the cylinder followed by a single vortex from the other side per T_l. The phenomenon involving the merging of vortices immediately behind the cylinder in the vortex shedding layers is also considered in this study. Following the notation of Reid (2010), this coalescence occurrence is denoted by an uppercase “**C**” that is written before the vortex shedding mode. For example, the designation **C(2S)** per T_l means that the alternate counter-rotating single vortex is shed from each side of the cylinder over T_l, where at least one of the shed vortices was formed by the coalescence of vortices either immediately behind the cylinder or within about 15 diameters. In addition, under certain circumstances, a switching in the vortex shedding mode in the near wake region may occur. Thus, a switching in the vortex shedding mode from **A**-mode to **B**-mode is denoted by **A** → **B**. It is worth mentioning that, in classifying these modes, only the near wake region is considered following the work of Ongoren and Rockwell (1988), while the notations of Williamson and Roshko (1988) are used. Notice that vortex shedding classification terminology employed has been recently used by several researchers such as Al-Mdallal et al. (2007), Al-Mdallal (2015) and Reid (2010).

The paper is arranged in the following sequence. In Section 2, we discuss the governing equations along with initial and boundary conditions. Section 3 deals with numerical algorithm and their finite difference discretizations. Section 4 deals with validation of our numerical scheme followed by results and discussion in Section 5. At the end, we summarize our observations in the concluding remarks.

2. Governing equations

We consider the two-dimensional unsteady, incompressible, viscous flow of a constant property Newtonian fluid over an infinitely long cylinder, whose axis coincides with the z-axis, placed horizontally in a cross-stream of an infinite extent. The two-dimensional flow configuration of the physical model is shown in Fig. 1. The fluid has a uniform stream with velocity U_∞. Here, R_0 denotes the radius of the circular cylinder, and R_∞ denotes radius of the circular far field boundary. At dimensional time $\tau = 0$, the sinusoidal rotational oscillation of the cylinder starts suddenly