Journal of Fluids and Structures 59 (2015) 394–405

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Streamwise oscillations of a cylinder beneath a free surface: Free surface effects on fluid forces

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ARTICLE INFO

Article history:
Received 7 May 2014
Accepted 20 August 2015
Available online 30 October 2015

Keywords:
Unsteady
Viscous incompressible
Free surface flow
Two-fluid model
Submerged oscillating cylinder
Fluid forces

ABSTRACT

A two-dimensional free surface flow past a circular cylinder forced to perform streamwise oscillations in the presence of an oncoming uniform flow is investigated at a Reynolds number of $R=200$ and fixed displacement amplitude, $A=0.13$, for the forcing frequency-to-natural shedding frequency ratios, $f/f_0=1.5, 2.5, 3.5$. The present two-fluid model is based on a velocity–pressure formulation of the two-dimensional continuity and unsteady Navier–Stokes equations. The continuity and Navier–Stokes equations are discretized using a finite volume approximation for two fluid regions. An improved volume-of-fluid method is employed to capture for the displacement of the free surface. The objective of this study is to examine the effects of the frequency ratios, $f/f_0=1.5, 2.5, 3.5$, and the cylinder submergence depths, $h=0.25, 0.5, 0.75$, on the fluid forces at a fixed Froude number of $\mathrm{Fr}=0.2$. The relationship between the changes in the wake dynamics of the cylinder described in Bozkaya et al. (2011) and in the properties of fluid forces is also discussed.

1. Introduction

The prediction of flow-related unsteady loading on circular cylinders is one of the fundamental steps in hydrodynamic design and control. In this context, the case of a submerged horizontal circular cylinder in a free surface flow has attracted a lot of research efforts. In the following, a summary of the state-of-the-art of these efforts are provided.

Miyata et al. (1990) examined steady translation of a cylinder through quiescent fluid when the cylinder placed beneath the free surface both experimentally and numerically. Their investigation is conducted at a Reynolds number of 4.96×10^4 for a Froude number (based on cylinder diameter) of approximately 0.24. Their work shows that shallowly submerged condition results in a smaller pressure reduction behind the cylinder. While their visualization suggests that the flow changes with time, there is no explicit evidence that shedding is observed. Sheridan et al. (1997) and Hoyt and Sellin (2000) conducted experiments to investigate the steady incident flow past a stationary cylinder close to a free surface using the PIV technique and dye tracer technique, respectively, for higher values of Froude number ($0.47 \le \mathrm{Fr} \le 0.72$). Sheridan et al. (1997) identified several classes of wake states which are different from those of the cylinder wake in an unbounded medium. In certain conditions, possible wake stage can exist only in a metastable form. That is, each state possesses limited stability such that time-dependent transformation from one state to another could occur in a self-sustaining fashion. Ohring

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http://dx.doi.org/10.1016/j.jfluidstructs.2015.08.006
0889-9746/

Nomenclature

$\mathbb{A}$	area open to flow
$\overrightarrow{a}$	acceleration of non-inertial frame of reference $(=(a_1, a_2, 0))$
A	forcing amplitude of the cylinder oscillation $(=A^*/d)$
C_L	lift coefficient $(=2L/\rho U^2 d)$
$C_{L,max}$	maximum lift coefficient
C_D	drag coefficient $(=2D/\rho U^2 d)$
$\widehat{C}_D$	mean drag coefficient
d	cylinder diameter
D	drag force per unit length
f	forcing frequency of the streamwise cylinder oscillation $(=df^*/U)$
f_0	natural vortex shedding frequency $(=df_0/U)$
Fr	Froude number $(=U/\sqrt{dg^*})$
$\overrightarrow{F}$	external force $(=(-a_1, 1/\mathrm{Fr}^2 - a_2, 0))$
$\overrightarrow{g}$	gravity force $(=(0, 1/\mathrm{Fr}^2, 0))$
h	depth of cylinder submergence $(=h^*/d)$
$\mathbb{I}$	length of a fluid-body interface open to flow
L	lift force per unit length
$\overrightarrow{n}$	outward unit normal vector $(=(n_1, n_2, 0))$
p	fluid pressure
R	Reynolds number $(=\rho Ud/\mu)$
S	control volume boundary
t	time $(=t^*U/d)$
Δt	time step
T	period of forced cylinder oscillation $(=1/f)$
$\overrightarrow{u}$	fluid velocity $(=(u, v, 0))$
U	uniform flow velocity
V	control volume
$\mathbb{V}$	volume open to flow

Greek Symbols

μ	dynamic viscosity of the fluid
ρ	fluid density
ν	kinematic viscosity of the fluid $(=\mu/\rho)$
Ω_i, $i=1,2$	fluid regions above and below the free surface, respectively
Ω	computational flow domain $(=\Omega_1 \cup \Omega_2)$

Superscripts

$*$	dimensional quantity

and Lugt (1991) showed that distortion of free surface combined with inherently time dependent shedding of vortices from the cylinder alters the nature of the absolute instability in a time dependent manner. Thus, changes in the behavior of the wake reported by Sheridan et al. (1997) can be linked to a change in the nature of the instability associated with the cylinder wake. This has important consequences for the forces on the cylinder. In the work by Ohring and Lugt (1991), the Froude number is maintained sufficiently low to avoid significant free surface distortions. Hoyt and Sellin (2000) confirmed some of the findings of Sheridan et al. (1997) and showed that the flow field is indeed time dependent. Reichl et al. (2005) have presented some results from computations of the flow, mainly focusing on the evolution of the vorticity field, the effects of submergence depth and Froude number together with details of the variation of physical parameters. They obtained good agreement with the experimental results of Sheridan et al. (1997) for higher Froude number cases.

An extraordinary feature of previous work is the enormous effort that has been expended on understanding of free surface flow past a stationary cylinder, with its attendant complex interplay between the vorticity flux from the free surface and the cylinder surface. All of the aforementioned studies were purely experimental investigations except the work by Miyata et al. (1990) and Reichl et al. (2005). Using a combination of qualitative flow visualization, force measurements and finite difference calculations, Miyata et al. (1990) discussed the relationship between vortex formation and the fluid forces on the cylinder. In their work, a sudden reduction in drag force with the decreasing depth of submergence was reported when the cylinder is located close to a free surface. An interesting finding is that the transverse force coefficient gradually decreases when the cylinder is placed further from the free surface, at sufficiently deep submergence, it takes on a nearly constant value for any further increases in submergence. In purely numerical study by Reichl et al. (2005), the two-dimensional flow is calculated using the computational fluid dynamics software package FLUENT 5, but no attempt was made to calculate unsteady fluid forces. Related investigations of a free surface wave past a stationary cylinder are summarized by Lin and Rockwell (1996) and Oshkai and Rockwell (1999). Considerable insight has been provided on various aspects of the unsteady loading, but no explicit link has been established between quantitative patterns of vorticity around the cylinder in the presence of an adjacent free surface.

Steady incident flow past streamwise oscillating circular cylinder beneath a free surface references may be made only to the works of Cetiner and Rockwell (2001b) and Bozkaya et al. (2011). The same problem is considered in the present study. Using PIV technique and simultaneous force measurements, Cetiner and Rockwell (2001b) investigated relationship between the flow patterns and the unsteady forces on the cylinder. It was found that the time-dependent transverse force was phase-locked to the cylinder motion and the vortex system occurred both upstream and downstream of the cylinder, provided that the cylinder is located immediately beneath the free surface. The submergence depth has remarkable consequences for the degree of variation in the force signatures, the averaged drag and lift forces, and the averaged spectra of the lift force. When the cylinder is located immediately beneath the free surface, it experiences substantial downward force (negative lift force) and, in some cases, the magnitude of the drag force can be decreased by as much as factor of 2. These findings are consistent with that of Miyata et al. (1990) for the uniform flow past a stationary (non-oscillating) cylinder case.