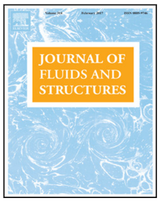
Journal of Fluids and Structures 77 (2018) 170–181

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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



Numerical study of vortex-induced vibrations of a flexible cylinder in an oscillatory flow

Bowen Fu, Lu Zou, Decheng Wan *

State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China

HIGHLIGHTS

- VIV of a flexible cylinder in an oscillatory flow is simulated using a CFD method;
- In-line vibrations are found to consist of three components;
- The butterfly-shaped trajectory has been observed;
- Wavelet analyses of vibrations and hydrodynamic forces have been conducted.

ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form 13 October 2017
Accepted 1 December 2017

Keywords:
Vortex-induced vibration
Oscillatory flow
Flexible cylinder
Viv-FOAM-SJTU solver
Fluid–structure interactions

ABSTRACT

The vortex-induced vibrations of a flexible cylinder oscillating harmonically in still water have been numerically simulated using a CFD method based on the strip theory. The algorithm PIMPLE in OpenFOAM is adopted to compute the flow field while the small-displacement Bernoulli–Euler bending beam theory is used to model the cylinder. Two ends of the flexible cylinder are forced to oscillate harmonically. The simulation results have been compared with experimental results and further analyzed. Features such as the hysteresis phenomenon and the build-up–lock-in–die-out cycle are observed in the cross-flow vibration. The in-line vibrations consist of three components, the low-frequency oscillation, the first-natural-frequency vibration during the cylinder reversal, and the second-natural-frequency vibration due to vortex shedding. The butterfly-shaped trajectory has been observed. Detailed wavelet analyses of the vibrations have been given at the end.

1. Introduction

A cylinder exposed to an oscillatory flow will experience vortex shedding if the Reynolds number and the Keulegan–Carpenter number are not too small, resulting in periodic variations in the force components on the cylinder. One feature of the cylinder exposed to an oscillatory flow is that the return of shedding vortices towards the cylinder after the flow reversal may cause a sudden change in the hydrodynamic forces. The in-line displacements primarily oscillate at the frequency of support motion, while small high-frequency periodic fluctuations are superimposed on the low-frequency displacements. These high-frequency fluctuations are induced by vortex shedding and vortex motions around the cylinder due to flow reversals. The case also applies to the in-line hydrodynamic forces. Vibrations will be amplified when the natural frequency is close to any of these vibration components, low-frequency oscillations or high-frequency fluctuations. When the amplitudes of the in-line oscillations become large, the in-line motions may begin to influence the cross-flow vibrations (Lipsett and Williamson, 1991). The cross-flow vibrations are generally of larger amplitudes.

---

* Corresponding author.
E-mail address: dcwan@sjtu.edu.cn (D. Wan).

https://doi.org/10.1016/j.jfluidstructs.2017.12.006

Nomenclature

$\boldsymbol{\phi}$	Mode shape
A_y	Amplitude of cross-flow vibration
$C_{\mathrm{H}x}$	In-line hydrodynamic force coefficient
$C_{\mathrm{H}y}$	Cross-flow hydrodynamic force coefficient
D	Diameter of the cylinder
$f_{\mathrm{H}x}$	In-line hydrodynamic force frequency
$f_{\mathrm{H}y}$	Cross-flow hydrodynamic force frequency
$f_{\mathrm{n}1}$	First natural frequency
$f_{\mathrm{n}2}$	Second natural frequency
f_{st}	Strouhal frequency
f_s^m	Frequency of modal weight of variable s
f_{w}	Support motion frequency
f_x	In-line vibration frequency
f_y	Cross-flow vibration frequency
L	Length of the cylinder
$\bar{s}$	Time-averaged value of the variable s
$s_{\max}$	Maximum value of the variable s
T	Tension of the cylinder
T_{w}	Support motion period
U_{r}	Reduced velocity
w_s^m	Modal weight of variable s
x	Relative in-line displacement
x_{s}	Support motion displacement
x_{t}	Total in-line displacement
y	Cross-flow displacement
z	Elevation

The hydrodynamic excitation of cylinders in oscillatory flows has been the subject of numerous investigations in the past several decades. Some researchers conducted experiments on the hydrodynamic response of rigid cylinders in oscillating flow (Kozakiewicz et al., 1994; Sarpkaya, 1979; Sumer and Fredsøe, 1988). From the experiment one of the typical characteristics of the response in oscillatory flows is the multi-peak behavior in the cross-flow amplitude responses (Kozakiewicz et al., 1997; Sumer and Fredsøe, 1988). A comprehensive review of the investigations can be found in Sumer and Fredsøe (1997). Some numerical investigations have also been conducted. Graham and Djahansouz (1991) used a discrete vortex method to predict the excitation of a cylinder in two directions. Anagnostopoulos and Iliadis (1998) used a finite element technique to study the cylinder response in the in-line direction. And more recently, Zhao (2013) conducted two-dimensional numerical studies of 2dof VIV of a circular cylinder in oscillatory flows, which reproduced some phenomena observed in experiments.

There is no much research on vortex-induced vibrations of flexible cylinders in oscillatory flows. Wang et al. (2014) conducted a series of experiments on this problem. In the present work, we investigate vortex-induced vibrations of a flexible cylinder subject to oscillatory flows using a computational fluid dynamics method, with parameters maintained identical to the model test by Wang et al. (2014) to facilitate comparison. The simulations are based on the in-house solver viv-FOAM-SJTU, which has been validated in previous studies (Duan et al., 2016; Fu et al., 2016; Wan and Duan, 2017). The present article is organized as follows. Section 2 introduces the concerned problems, followed by the simulation methods in Section 3 for handling the problems in Section 2. And Section 4 gives the simulation results with detailed analyses. Finally, a curt summary is presented in Section 5.

2. Problem

As regards oscillatory flows, there are two approaches to form them. In one, oscillatory flows are created by driving the water. For example, in the study of Sarpkaya (1986), a U-shaped oscillating flow tube was used. While in most other research, an oscillating cylinder is adopted. In both the experiment of Wang et al. (2014) and the present simulation, the oscillatory flow is formed by forcing two ends of the cylinder to oscillate harmonically. The main parameters of the experiment are listed in Table 1 and are maintained identical in the simulation. The mass ratio m^* in Table 1 denotes the ratio of the mass of the cylinder to the mass of the displaced water. Depicted in Fig. 1 is the experimental setup. The support motion is a periodic