Journal of Fluids and Structures 43 (2013) 110–123

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Modal characteristics of a flexible cylinder in turbulent axial flow from numerical simulations

Jeroen De Ridder[a,*], Joris Degroote[a], Katrien Van Tichelen[b], Paul Schuurmans[b], Jan Vierendeels[a]

[a] Department of Flow, Heat and Combustion Mechanics, Faculty of Engineering and Architecture, Ghent University, Ghent, Belgium
[b] Belgian Nuclear Research Centre, Mol, Belgium

ARTICLE INFO

Article history:
Received 12 December 2012
Received in revised form
12 August 2013
Accepted 2 September 2013
Available online 3 October 2013

Keywords:
Flow-induced vibrations
Fluid–structure interaction
Eigenmode

ABSTRACT

In this paper the vibration behavior of a flexible cylinder subjected to an axial flow is investigated numerically. Therefore a methodology is constructed, which relies entirely on fluid–structure interaction calculations. Consequently, no force coefficients are necessary for the numerical simulations. Two different cases are studied. The first case is a brass cylinder vibrating in an axial water flow. This calculation is compared to experiments in literature and the results agree well. The second case is a hollow steel tube, subjected to liquid lead–bismuth flow. Different flow boundary conditions are tested on this case. Each type of boundary conditions leads to a different confinement and results in different eigenfrequencies and modal damping ratios. Wherever appropriate, a comparison has been made with an existing theory. Generally, this linear theory and the simulations in this paper agree well on the frequency of a mode. With respect to damping, the agreement is highly dependent on the correlation used for the normal friction coefficients in the linear theory.

1. Introduction

Flow-induced vibrations are an important concern in the design of tube bundles. Typically, fluid-elastic instabilities occur in cross flow conditions (Pettigrew and Taylor, 2003), although axial flow conditions are also known to trigger these instabilities (Wang and Ni, 2009). The dynamics of slender cylinders submerged in axial flow has already been studied for a long time: work on the added mass of two concentric cylinders dates back to Stokes (1843). The expression for the confinement effect which he derived can still be found in current text books (Chen, 1987; Païdoussis, 2004; Au-Yang, 2001).

Many of the analytical models for slender cylinders or related structures in axial flow that are used nowadays (Chen, 1987; Païdoussis, 1973; de Langre et al., 2007; Païdoussis et al., 2007; Sakuma et al., 2008; Rinaldi and Païdoussis, 2012) are mainly based on motion-induced inviscid forces (Lighthill, 1960) and are thus not based on the full Navier–Stokes equations. The effect of the viscous hydrodynamic forces is added afterwards. While the inviscid forces are derived from potential flow theory, the viscous forces are often introduced with empirical coefficients. A review on most of the available models can be found in Païdoussis (2004). The current analytical approach performs well for the frequency prediction, but the prediction of flutter type instabilities or turbulence-induced vibrations requires a good prediction of damping, which is governed by the viscous forces normal to the cylinder and thus by the mainly empirical coefficients. Therefore, research on these normal

* Corresponding author. Tel.: +32 9 264 32 97.
E-mail address: j.deridder@ugent.be (J. De Ridder).

0889-9746/$ - see front matter
http://dx.doi.org/10.1016/j.jfluidstructs.2013.09.001

forces is still ongoing (Ersdal and Faltinsen, 2006; Divaret et al., 2012). To improve the accuracy of the predictions in annular flow, some computational research was performed as well. Belanger et al. (1994) e.g. developed a model to numerically investigate the dynamics of cylinders in laminar annular flow and Perotin and Granger (1997) developed a linear computational model for a cylinder in turbulent annular flow.

Alternative computational approaches to the coupled method, which will be used in this paper, would be to either compute the viscous force coefficients required in linear theory (Phan et al., 2013; Facci and Porfiri, 2013) or directly measure modal matrices from a harmonically prescribed motion, which is typically performed for cross-flow fluidelastic instabilities. The first strategy has however the downside that all the viscous effects should be captured by the empirical formulations. The latter strategy has the disadvantage that modal matrices are determined at a fixed frequency of oscillation, not necessarily equal to an eigenfrequency. Modal damping is however dependent on the frequency of oscillation (Chen, 1987). Therefore, this forced displacement method should be performed with multiple frequencies. Transfer functions should be determined from these responses, followed by a determination of mass, damping and stiffness matrices if possible (Goyder, 2002). This however requires a lot of calculations.

The goal of this paper is to compute modal characteristics of a single tube subjected to turbulent axial flow without empirical formulations for the viscous forces. The results for this geometry are readily compared to experimental results and existing theories. A methodology which allows the determination of modal characteristics from partitioned fluid–structure interaction (FSI) simulations will be proposed in the first part of this paper. These FSI-simulations are based on a combination of computational structural mechanics (CSM) and computational fluid mechanics (CFD). In the second part, the results of the computational method will be validated with modal characteristics of water experiments available in literature (Chen and Wambsganss, 1972). Finally the methodology will be applied to a hollow tube, vibrating in liquid Pb–Bi eutectic. This configuration originates from the design of the MYRRHA reactor, which is currently being developed as a prototype nuclear reactor of the 4th generation (Abderrahim et al., 2010).

2. Methodology

In this section, it will be explained how to compute the first N_m eigenmodes, natural frequencies and modal damping ratios of a structure in a fluid from numerical simulations. The methodology consists of several steps (see Fig. 1) with a flow solver for the fluid domain around the tubes and a structural solver for the tubes themselves.

Initially a finite element solver is used to solve the pure structural eigenmode problem. The damping in the structure is neglected, as, in the cases considered here, it is smaller than the damping due to the fluid; hence

$$(K-\omega_i^2 M)\phi_i = 0, \tag{1}$$

with K the stiffness matrix, M the mass matrix and ω_i the eigenfrequency of eigenmode ϕ_i. The mode shape ϕ_i is scaled such that the maximal displacement is 1(−). One of these mode shapes, ϕ_i, is then used as a rigid wall boundary condition in a steady flow simulation. The position of the fluid–structure interface x_s in this calculation is thus given by

$$x_s = X_s + \alpha\phi_{i,s}, \tag{2}$$

where X_s is the original position of the interface, $\phi_{i,s}$ the structural mode shape restricted to the common surface of the fluid and the structure and α a scaling factor. The third and final step consists of an unsteady FSI simulation, in which the free

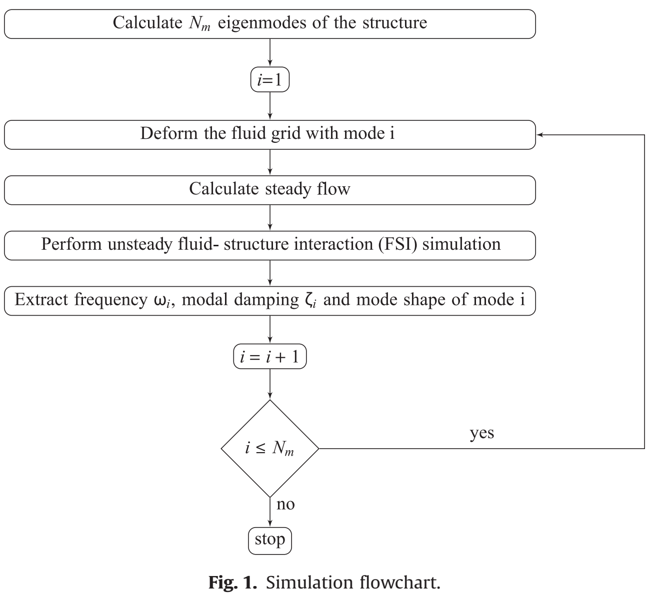

Fig. 1. Simulation flowchart.