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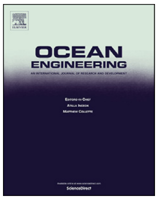

A novel reduced order model for vortex induced vibrations of long flexible cylinders

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ABSTRACT

In this manuscript the development of a reduced order model for the analysis of long flexible cylinders in an offshore environment is proposed. In particular the focus is on the modelling of the vortex induced vibrations (VIV) and the aim is the development of a model capable of capturing both the in-line and cross-flow oscillations. The reduced order model is identified starting from the results of a high fidelity solver developed coupling together a Finite Element Solver (FEM) with a Computational Fluid Dynamics (CFD) solver. The high fidelity analyses are conducted on a reduced domain size representing a small section of the long cylinder, which is nevertheless, already flexible. The section is forced using a motion which matches the expected motion in full scale, and the results are used for the system-parameter identification of the reduced order model. The reduced order model is identified by using a system and parameter identification approach. The final proposed model consists in the combination of a forced van der Pol oscillator, to model the cross-flow forces, and a linear state-space model, to model the in-line forces. The model is applied to study a full scale flexible model and the results are validated by using experiments conducted on a flexible riser inside a towing tank.

1. Introduction

Due to the gradual depletion of oil and gas resources onshore and in shallow waters, recent years have seen an increasing interest in deeper waters, where a large proportion of the remaining oil and gas is located. The recent interest in deeper waters comes not only from the petroleum industry but also from the renewable energy sector. The sea, especially in deep waters, has a huge energy potential, which could be exploited using wave energy converters, solar power plants and wind turbines located on offshore platforms. Long slender cylinders are found in many offshore applications and are the representative system for mooring lines, risers, umbilicals and free spanning pipelines in deep water. The responses of these kinds of structures to wave, current and tide loads may be complex, and phenomena such as vortex induced vibrations, unsteady lock-in, dual resonance, and travelling waves response may occur (Wu et al., 2012). Much progress has been made to understand the hydrodynamic forces that have to be used for these structures but an efficient and reliable model, especially dealing with vortex induced vibrations (Sarpkaya, 2004), is still missing in literature. Computational fluid dynamics (CFD) methods have been demonstrated to be a possible way of getting the response of flexible structures in an offshore environment, especially considering the increasing of the available computational power, but they are still not applicable to long-term simulations and to values of the Reynolds number interesting for practical applications.

Although in the future CFD methods will probably be the first choice for design purposes, at the moment we still have to rely on simplified and approximated methods mostly based on experimental investigations conducted on rigid cylinders undergoing forced or free vibrations (Sarpkaya, 2004; Williamson and Govardhan, 2008, 2004). This contribution aims to develop a new time domain simplified method identified through high-fidelity FSI simulations conducted on flexible cylinders undergoing forced oscillations.

The paper is organised as follows: in section 2 a brief overview regarding VIV phenomena and existing methods for their simulations is presented, in section 3 the methods used for the evaluation of the reduced order method are introduced. Section 4 describes the fluid-structure interaction solver developed and used for the high fidelity analyses. In section 5 the ROM proposed in this manuscript is described and in section 6 numerical tests are presented and discussed. Finally in section 7 some conclusions are drawn and perspectives for future works are provided.

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Abbreviations and symbols

Abbreviations

ALE	Arbitrary Lagrangian Eulerian
CFD	Computational fluid dynamics
CTL	Component Template Library
DFMT	Direct Force-Motion Transfer
DNS	Direct Numerical Simulation
FEM	Finite Element Method
FSI	Fluid Structure Interaction
FVM	Finite Volume Method
LES	Large Eddy Simulation
PEM	Prediction Error Method
POD	Proper Orthogonal Decomposition
RANS	Reynolds-averaged Navier-Stokes
ROM	Reduced Order Model
SISO	Single Input Single Output
VDP	van der Pol
VIV	Vortex Induced Vibrations
CF	Cross-Flow
IL	In-Line

Symbols

$\boldsymbol{u}_{fs}$	free stream velocity
D	cylinder diameter
d	general letter to indicate the displacement of the cylinder
D'_c	Fluctuating part of the Drag Coefficient
D_c	Total Drag Coefficient
$D_{c,m}$	Mean part of the Drag Coefficient
d_{IL}	d_{CF} displacements along the *IL* and *CF* directions
f_v	frequency of vortex shedding
L	Lenght of the cylinder
L_c	Lift Coefficient
Re	Reynolds Number
St	Strohual Number

2. Brief overview on the VIV phenomenon

Long flexible cylinders in an offshore environment are often exposed to the phenomena of vortex-induced vibrations (VIV). VIV are an important phenomenon in many different engineering fields and have been studied in either air or water for many years. The content of this section is summarized from the numerous reviews on the topic available in literature (Williamson and Govardhan, 2004, 2008; Sarpkaya, 2004; Wu et al., 2012; Gabbai and Benaroya, 2005). This phenomenon is caused by the oscillating flow arising from the alternate vortex shedding. Among all possible existing phenomena that may happen on flexible cylindrical structures in an offshore environment, VIV are one of the most dangerous and hard to predict. If a rigid and fixed cylinder is considered, frequency of the vortex shedding phenomenon follows the Strouhal law (Strouhal, 1878):

$$St = \frac{f_v D}{U} \tag{1}$$

in which St is the Strouhal number, f_v is the frequency of the vortex shedding, and U is the free stream velocity.

For a rigid and fixed circular cylinder the Strouhal number, over a certain range of the Reynolds number, assumes a constant value approximately equal to 0.2. In this range of values, which are particularly interesting for practical applications, the relationship between the free stream velocity and frequency of oscillation is linear. Conversely, if it is considered a cylinder which is free to vibrate or forced to move the phenomenon does no longer obey the Strohual law (Strouhal, 1878). When the vortex shedding frequency approaches the natural frequency the so called lock-in phenomenon is observed. The synchronisation of the vortex shedding frequency to the frequency of oscillation occurs over a certain range of the flow velocity. In this range the vortex shedding phenomenon is driven by the frequency of oscillation of the cylinder.

2.1. Literature survey on VIV modelling

Although a lot of research has been performed in this field, three basic different methods to predict the behaviour of a slender cylinder subjected to VIV can be found:

- Semi-empirical models
- Navier-Stokes models
- Simplified wake models

Here the methods are only briefly introduced and discussed, a comprehensive review regarding these different approaches and a comparison of their results can be found in Chaplin et al. (2005).

2.1.1. Semi-empirical models

These methods are widely used by numerous authors and are nowadays the standard for many commercial codes used in offshore engineering such as VIVA (Triantafyllou, 2003; Zheng et al., 2011), VIVANA (Larsen et al., 2001a, b), SHEAR7 (Vandiver, 1993; Vandiver and Li, 2005). The instantaneous amplitude of oscillation is evaluated using appropriate force coefficients. These are evaluated on experimental tests on rigid cylinders undergoing free or forced vibrations. The assumption of only cross flow motion is made. In these approaches it is normally assumed that the cylinder is oscillating only in cross-flow direction and when also the in-line oscillation is considered it is assumed to be decoupled respect to the cross-flow motion. Within this method, natural frequencies of the structure are evaluated and than the modes which are most likely to be excited by the vortex shedding are identified. Normally only the steady in-line response of the structure is identified. The main limitation of this category of models is that they make the assumption of only cross-flow motion and, since they operate in the frequency domain, they are not able to capture non-linearities. These tools also make the assumption of a harmonic motion and the solution is given by a superposition of different oscillation modes.

2.1.2. CFD models

In CFD methods the flow field around the cylinder is computed by solving numerically the unsteady Navier-Stokes equations. Bourguet et al. (2011b, a) proposed a full three dimensional analysis of a long flexible cylinder. In these works the authors coupled a structural code with a CFD solver with direct numerical simulation of three dimensional unsteady Navier-Stokes equations, and the structural response is investigated. Boyer et al. (2011) used a geometrically-exact beam model for the coupling with a CFD code which solves the unsteady incompressible Reynolds-averaged Navier-Stokes equations enabling vortex induced vibration configurations to be handled. In his PhD thesis, Huang (2011) investigated the vortex shedding on a riser. He used a direct FEM integration solver for the structural dynamic and an unsteady incompressible Navier-Stokes solver with a LES turbulence model for the fluid dynamic. A complete review on numerical methods for VIV is also presented in his thesis. Akhtar (2008) performed several high-fidelity CFD analyses with Navier-Stokes DNS methods in order to represent the flow field with few dominant modes using a POD. The emphasis is here given to the control of VIV using fluid actuators. Gallardo et al. (2014) applied POD, after