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Numerical simulation of vortex-induced motion of a deep-draft paired-column semi-submersible offshore platform

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ABSTRACT

Understanding and predicting vortex-induced motion (VIM) of offshore systems for deep seawater applications is crucial to improve the system safety and integrity. We report on experimental tow-tank measurements and numerical simulations of VIM of a deep-draft offshore platform, specifically Paired-Column Semisubmersible (PC-Semi). The study is carried out in model scale (1:54), at subcritical flow regime with $Re \sim 10^4$. Motion of the floating structure has three degrees of freedom: in-line, cross-flow, and yaw. Large periodic cross-flow motion is measured for headings 0°, 11.25°, and 22.5°, for reduced velocities (U_r) between 5 and 10. Considerably smaller cross-flow amplitude is recorded at 45° heading across the U_r range considered.

An extensive sensitivity study is performed using computational fluid dynamics (CFD) to capture the transient displacement history of VIM (in-line, cross-flow, and yaw motion components). Amplitude and period of cross-flow (transverse) motion are obtained from statistical analysis of VIM time history and subsequently used as the validation criterion between the CFD simulation and the model tests. Satisfactory agreement between the CFD results and tow-tank measurements is achieved with a Delayed Detached Eddy Simulation – Shear Stress Transport (DDES-SST) formulation. This work provides experimental results and serves as a practical starting point to set up a CFD problem to estimate amplitude and period of cross-flow VIM motion for offshore engineering applications.

1. Introduction

Fluid-structure interactions (FSI) caused by vortex shedding in fluid flow around solid objects are encountered across many engineering applications, including bridges, buildings, chimney stacks, vibrating tubes in heat exchangers, and aerial-, terrestrial-, and aquatic-vehicles. In particular, this work focuses on the large-amplitude motion of a tethered offshore structure induced by periodic vortex shedding from its pillars (von-Karman vortex streets).

A bluff body immersed in a stream of fluid is susceptible to vortex resonance and galloping instabilities, especially when its natural frequency coincides with the vortex-shedding frequency. Recent years have shown an increasing interest in the response of offshore floaters to the action of sea currents (Waals et al., 2007; Guoxing et al., 2006; Goncalves et al., 2013; Jaime et al., 2013). Nevertheless, accurate prediction of vortex-induced vibration or motion (VIV or VIM) has proven difficult owing to nonlinear fluid forces and feedback between cylindrical pillars (or columns of a multi-column floater) and the fluid flow (Blevins, 2009; Goncalves et al., 2012).

The trend in offshore oil exploration has been to move into deeper water to satisfy the increasing energy demands and exploit reserves in deep and ultra-deep water, such as the deep-water regions in the Gulf of Mexico (GoM). Depending on the water depth and oil production system design, wet tree (subsea) or dry tree (surface) (Lee et al., 2014; Lim, 2009), the industry uses a few predominant platform design concepts: tension-leg platforms (TLPs), spars, and semisubmersibles (Halkyard, 2005; Antony et al., 2015). The study of VIM of offshore platforms has become of utmost importance since many regions experience strong loop

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Nomenclature

Acronyms

ALE	Arbitrary Lagrangian-Eulerian
CFD	Computational Fluid Dynamics
CFL	Courant-Friedrichs-Lewy condition
DDCSF	Deep-Draft Column-Stabilized Floater
DDES	Delayed Detached Eddy Simulation
DTS	Dry-tree semisubmersible
GoM	Gulf of Mexico
DDES-SST	DDES Shear Stress Transport (turbulence model)
DDES-SA	DDES Spalart Allmaras (turbulence model)
RPSEA	Research Partnership to Secure Energy for America (www.rpsea.org)
URANS	Unsteady Reynolds-Averaged Navier Stokes
VIM	Vortex Induced Motion
PC-Semi	Paired-Column Semisubmersible

Arabic symbols

A	Amplitude of transverse (cross-flow) oscillation (m)
A_{nom}	Nominal Amplitude (m)
$(A_{\text{nom}}/\text{D})$	Normalized nominal amplitude (–)
c	Yaw chord (m)
D	Characteristic length (m): diagonal of the outer column of a semisubmersible (or side of column for a single-column study)
Fr	Froude number
F_{su}	In-line force (N)
F_{sw}	Cross-flow force (N)
f	Natural frequency (Hz)
f_s	Vortex Shedding frequency (Hz)
k	Spring constant (kN/m)
L	Generic length dimension
M	Generic mass dimension
M	Moment (Nm)
m	Slope in the Fey et al. relation (dimensionless)
P	Natural period (s)
p	Pressure (Pa)
R	Yaw radius (m)
Re	Reynolds number (dimensionless)
St	Strouhal Number (dimensionless)
T	Generic time dimension
Tz	Average Zero Crossing Period (s)
t	Time (s)
U_r	Reduced Velocity (dimensionless)
U_∞	free stream velocity (m/s)
u_i	*i*-th velocity component (m/s)
x	Direction of in-line response (m)
x_i	*i*-th spatial coordinate (m)
y	Direction of cross-flow response (m)
y_{w}	Normal distance from a solid wall (m)
y^*	Viscous length scale (m)
y^+	Normal distance from a solid wall in “wall units” (dimensionless)

Greek symbols

γ	Specific weight (N/m^3)
Δs	mesh size (m)
Δt	time step (s)
δ_{ij}	Kronecker delta
ν	Kinematic viscosity (m^2/s)
ν_t	Turbulent viscosity (m^2/s)
ρ	Fluid density (kg/m^3)
ϱ	Ratio of specific weights
τ_{w}	Wall shear stress (N/m^2)
Ψ	Generic angle
ψ	Yaw angle (rad)

currents (e.g. deepwater region of GoM), which trigger resonant motions due to vortex shedding. For instance, in moderate water depth (up to around 1500 m), spar (mono-column design) platforms have proven so far to be a satisfactory solution for oil exploration. However, the single cylindrical shape of platform (or, a mono-column) with high level of current speeds is susceptible to synchronized vortex shedding that induces oscillatory motion with relatively high amplitude (on the order of the cylinder's diameter).

In the Gulf of Mexico, extreme water depths beyond 1800 m are dominated by Semi-submersibles (Antony et al., 2015). This design, also known as a “semi”, has drawn a lot of attention for deep-water reservoir development due to large payload capacity and quayside integration feasibility. There are two main types of Semi-submersible design: (a) a four-column platform (also known as conventional semi, or C-semi) already deployed and operating, and (b) an eight-column platform (also known as paired-column, or PC-Semi), which is still in development stage. While the latter design is the main focus of this study, our results also shed light on the behavior of the C-semi design. The PC-Semi is specifically targeted at dry tree applications in the Gulf of Mexico as an alternative to the Spar concept in deep and ultra-deep water development (depth beyond 1800 m). The philosophy of developing the PC-Semi concept is to utilize conventional designs of hull structure, tensioner systems (already developed spar like ram-style tensioner), and well-bay arrangements, and to maintain quayside integration to avoid extensive offshore installation cost and risk (Zou et al., 2013).

As shown in Fig. 1, the PC-Semi has eight rectangular columns with rounded corners arranged in pairs at each of the 4 corners. The inner columns are thinner than the outer columns. Also, the PC-Semi draft is deeper and the slenderness ratio is larger than a conventional semi-submersible. In general, larger column slenderness ratio is likely to make the structure more susceptible to VIM. Thus, it is anticipated that the PC-Semi has unique VIM response characteristics (Zou et al., 2013). Previous survey of the open literature showed that nominal amplitude of cross-flow VIM motion can be substantially lower in PC-Semi designs compared to the C-Semi designs (Vinayan et al., 2015). While there is a reasonable body of work related to conventional semis (Goncalves et al., 2012, 2013; Ma et al., 2014; Zeng et al., 2014; Lie et al., 2016), and even more so related to spars (Halkyard et al., 2005, 2006; Lefevre et al., 2013; Fujiwara et al., 2013), only limited amount of work is available in open literature related to VIM response of a PC-Semi since it is a more recent design concept.

Periodic VIM motion, manifested through large displacements and drift on the sea surface imposes important static and fatigue loads on the mooring lines and riser system (Ma et al., 2013). Over time, VIM can impact the integrity of vital offshore system components and the overall system safety. As a response, VIM has emerged as an important issue in offshore engineering for oil exploration in ultra-deep water (Antony et al., 2015) as well as for offshore wind turbine platforms (Fujiwara et al., 2013). As measurements from the offshore field are mainly proprietary and limited, one must rely on model-scale tow tank testing and CFD simulations to study VIM. In general, there is a need for a well-defined benchmark framework to compare the full-scale field data (prototype scale) to the model-scale results and developing experimentally validated, practical CFD methodology for applications in model