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Experimental investigation of the flow-induced vibration of a curved cylinder in convex and concave configurations

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ABSTRACT

Experiments have been conducted to investigate the two-degree-of-freedom vortex-induced vibration (VIV) response of a rigid section of a curved circular cylinder with low mass-damping ratio. Two curved configurations, a concave and a convex, were tested regarding the direction of the flow, in addition to a straight cylinder that served as reference. Amplitude and frequency responses are presented versus reduced velocity for a Reynolds number range between 750 and 15 000. Results for the curved cylinders with concave and convex configurations revealed significantly lower vibration amplitudes when compared to the typical VIV response of a straight cylinder. However, the concave cylinder showed relatively higher amplitudes than the convex cylinder which were sustained beyond the typical synchronisation region. We believe this distinct behaviour between the convex and the concave configurations is related to the wake interference taking place in the lower half of the curvature due to perturbations generated in the horizontal section when it is positioned upstream. Particle-image velocimetry (PIV) measurements of the separated flow along the cylinder highlight the effect of curvature on vortex formation and excitation revealing a complex fluid–structure interaction mechanism.

1. Introduction

Ongoing deep-sea exploration, installation and production of hydrocarbon energy need the development of new viable technologies. One of these is the requirement of a robust and reliable analysis tool for the prediction of vortex-induced vibration (VIV) of marine structures exposed to ocean currents. Because VIV can cause high cyclic-loading fatigue damage of structures, it is now widely accepted to be a crucial factor that should be taken into account in the preliminary analysis and design. However, many insightful VIV aspects are still unknown and far from fully understood; these render the structural design quite conservative with the use of a large factor of safety. For offshore structures with initial curvatures and high flexibility such as catenary risers, mooring cables and free-spanning pipelines, the theoretical, numerical or experimental VIV research is still very lacking.

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Nomenclature

D	cylinder external diameter
f_0	natural frequency in air
f_x	streamwise oscillation frequency
f_y	cross-flow oscillation frequency
h	cylinder vertical length below the water line
m^*	mass ratio
Re	Reynolds number
U	flow speed
U/Df_0	reduced velocity
$\hat{x}$	streamwise harmonic amplitude of vibration
$\hat{y}$	cross-flow harmonic amplitude of vibration
ζ	structural damping ratio

Risers are very long pipes used to carry oil from the sea bed to offshore platforms floating on the water surface. Under the effect of sea currents, these flexible structures are especially susceptible to flow-induced vibrations, particularly since they have a relatively low mass compared to the mass of the displaced fluid. Generally, an offshore floating platform accommodates several riser pipes together with many other cylindrical structures. The interaction of these flexible structures can produce an even more complex problem, resulting in vibrations with rather unexpectedly higher amplitudes (Assi et al., 2010a). Flow interference from the platform hull, the soil on sea bed and the pipe itself can also increase the complexity of the flow, generating complex responses.

The riser may respond with different amplitudes and frequencies depending on the flow excitation and structural stiffness along the length of the pipe. Consequently, several modes of vibration with varying curvature appear along the span resulting in a very rich fluid–structure interaction mechanism (Srinil, 2010). In addition to that, flexible risers can be laid out in a catenary configuration which results in high curvature close to the region where it touches the bottom of the ocean, called the touchdown point.

In an attempt to understand and model the fluid-dynamic behaviour around curved sections of risers we have performed experiments with a curved, rigid circular cylinder in a water channel. This idealised experiment is far from reproducing the real conditions encountered in the ocean; nevertheless it should throw some light on understanding how the vortex shedding mechanism is affected by the curvature of the pipe. In addition to the phenomenological aspects, the present work may also serve as reference for validation and benchmarking of numerical simulations of fluid–structure interaction.

An investigation into the vortex shedding patterns and the fundamental wake topology of the flow past a stationary curved circular cylinder has been carried out by Miliou et al. (2007) and de Vecchi et al. (2008, 2009) based on computational fluid dynamics studies. As a result of pipe initial curvatures, flow visualisations highlight different kinds of wake characteristics depending on the pipe (convex or concave) configuration and its orientation with respect to (aligned with or normal to) the incoming flow. When the flow is uniform and normal to the curvature plane, the cross-flow wake dynamics of curved pipes behave qualitatively similar to those of straight pipes. This is in contrast to the case of flow being aligned with the curvature plane where wake dynamics change dramatically. However, these scenarios are pertinent to a particular stationary cylinder case in a very low-Reynolds number range. The VIV behaviour will further transform if the structure oscillates and interacts with the fluid wakes, depending on several fluid–structure parameters.

2. Experimental arrangement

Experiments have been carried out in the Circulating Water Channel of the NDF (Fluids and Dynamics Research Group) at the University of São Paulo, Brazil. The NDF-USP water channel has an open test section 0.7 m wide, 0.9 m deep and 7.5 m long. Good quality flow can be achieved up to 1.0 m/s with turbulence intensity less than 3%. This laboratory has been especially designed for experiments in flow-induced vibrations and more details about the facilities are described in Assi et al. (2006).

A rigid section of a curved circular cylinder, with an external diameter of $D=32$ mm, was made of ABS plastic and Perspex tubes according to the dimensions shown in Fig. 1. The curved cylinder was composed of a horizontal section with $10D$ in length, a curved section with a $10D$ radius and a vertical section with length h/D that could be varied with reference to the water line. The water level was set to 700 mm from the floor of the channel, which meant that the $10D$-long horizontal part of the cylinder was not close enough to the floor to suffer interference from the wall.

The model was connected by its upper end to a long pendulum rig (length $H=3.0$ m) that allowed the system to oscillate in two degrees of freedom (2-dof) in the cross-flow and streamwise directions. The model was attached to two pairs of coil springs that provided the stiffness of the system. The springs were set to provide the same natural frequency (f_0, measured in air) in both the cross-flow and streamwise directions. The design and construction of the pendular elastic rig was made by Freire and Meneghini (2010) based on a previous idea employed by Assi et al. (2009, 2010b) for experiments with VIV suppressors. The present apparatus has been validated for VIV experiments by Freire et al. (2009, 2011).

Two laser sensors measured the cross-flow and streamwise displacements of the pendulum referring to the displacement of the bottom tip of the models. A load cell was installed before the springs to allow for instantaneous measurements of lift and drag acting on the cylinder. (Hydrodynamic forces will not be discussed in this paper.) A particle-image velocimetry (PIV) system was employed to analyse the instantaneous wake patterns along the cylinder span.