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Vortex and wake-induced vibrations of a tandem arrangement of two flexible circular cylinders with near wake interference

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ABSTRACT

Results showing the dynamic response of a tandem arrangement of two vertical high aspect ratio (length over diameter) and low mass ratio (mass over mass of displaced fluid) flexible cylinders vibrating at low mode number are presented in this paper. Two circular cylinder models were aligned with the flow, so the downstream or trailing cylinder was immersed in the wake of the leading one. Centre-to-centre distances from 2 to 4 diameters were studied. The models were very similar in design, with external diameters of 16 mm and a total length of 1.5 m. Reynolds numbers up to 12 000 were achieved with reduced velocities, based on the fundamental natural frequency of the downstream cylinder in still water, up to 16. The trailing model had a mass ratio of 1.8 with a combined mass-damping parameter of 0.049, whilst the corresponding figures for the leading cylinder were 1.45 and 0.043, respectively. The dynamic response of the trailing model has been analysed by studying cross-flow and in-line amplitudes, dominant frequencies and modal amplitudes. The dynamic response of the leading one is analysed by means of its cross-flow amplitudes and dominant frequencies and it is also related to the motion of the trailing cylinder by studying the synchronisation between their instantaneous cross-flow motions. Planar digital particle image velocimetry (DPIV) was used to visualise the wake. Different response regimes have been identified based on the type of oscillations exhibited by the cylinders: vortex-induced (VIV), wake-induced (WIV) or combinations of both.

1. Introduction

Slender marine structures such as riser pipes, mooring lines and subsea pipelines are often exposed to currents in arrangements involving several elements. Tandem, side-by-side and staggered configurations of long flexible circular structures are widely used especially by the oil industry in deep water operations. When bluff structures are immersed in the wake of other bluff bodies, interference exists and their dynamic responses become very different to what would be expected if isolated. An excellent pioneering work describing the flow around stationary cylinders with wake interference has been presented by Zdravkovich (1987, 1997). The author classified the different types of clusters and the flow regimes found, focusing on the proximity interference (side by side) and the wake interference (tandem and staggered) cases. Discussions on the different theoretical models for fluidelastic instabilities of cylinder arrays have been presented by Païdoussis (1981), Païdoussis and Price (1988) and Price (1995). Recent work demonstrates that there is still a large interest in the wake interference regime for stationary cylinders (Sumner et al., 2000; Lin et al., 2002; Xu and Zhou, 2004; Hu and Zhou, 2008), a fact that appears evidenced with the very recent publication of a review article by Sumner (2010).

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The problem of tandem cylinder wake interference has been approached by many researchers through studying the response of a cylinder immersed in the perturbed flow generated by an upstream stationary cylinder (Bokaian and Geoola, 1984; Hover and Triantafyllou, 2001; Assi et al., 2006). Zdravkovich (1985) showed results for side by side, staggered and tandem pairs of flexibly mounted rigid cylinders. Vortex-induced vibrations, wake-induced galloping and combinations of both types of response were observed by Bokaian and Geoola (1984) in experiments with a flexibly mounted rigid cylinder immersed in the wake of an identical fixed one. The authors varied both the longitudinal and lateral positions of the downstream cylinder and presented measurements of Strouhal numbers, time mean lift and drag force coefficients and the dynamic response of the trailing cylinder. Zdravkovich (1985) observed several flow-induced responses for the case of tandem arrangements at the different separations he tested. With very small centre-to-centre separations (up to 1.1) the two bodies acted as a single one. For slightly larger separations (up to 1.6) there was still a single vortex street and alternating reattachment of the shear layers from the upstream cylinder on to the downstream one was observed. It was from about 2.5 and up to 4 diameters where a bistable regime was found, indicating the minimum separation necessary for having a regular vortex street shed from the upstream cylinder. In this bistable regime he found that the upstream cylinder responded with considerably larger amplitudes than the rear one. For distances of more than 4 diameters, with vortex shedding from each cylinder, he observed that the front cylinder responded irregularly with less amplitude that the rear one which showed large amplitude regular motion.

Mahir and Rockwell (1996) used forced oscillations to study phase locked vortex patterns in the wake of the system for different spacings. Hover and Triantafyllou (2001) carried out an experiment involving interference between a fixed upstream cylinder and a downstream one free to vibrate in the transverse direction. They used a separation of 4.75 diameters since this was where Zdravkovich (1985) found the largest motions. Measurements of amplitudes and drag and lift coefficients were made and they observed a response dominated by what they described as galloping-like behaviour. Assi et al. (2006) also reported a galloping type of behaviour for a tandem arrangement with a fixed upstream cylinder and a downstream one constrained to move only in the cross-flow direction. The response was very similar to that reported by Hover and Triantafyllou (2001) but DPIV results were also presented. In both experiments, the cylinders were lightly damped and had a low mass ratio, but Assi et al. (2006) studied four gap distances from 2 to over 5.5 diameters rather than the one investigated by Hover and Triantafyllou (2001). They suggested that the oscillations were mainly galloping-like and described the phenomenon as ''wake-interference vibrations'' to account for the fact that the large motions observed in the downstream body were partly caused by vortex shedding and enhanced by the vortices shed from the upstream cylinder.

Brika and Laneville (1997, 1999) and Laneville and Brika (1999) compared results of a fully flexible cylinder in the wake of a fixed one in tandem, with results for both cylinders free to vibrate in tandem for large separations. All the experiments were carried out in a wind tunnel and separations in the range from 7 to 25 diameters were studied. Compared to an isolated cylinder, they found for the downstream cylinder an increase in the reduced velocity for the onset of oscillations and a wider response region. Maximum amplitudes decreased as the separation between the cylinders increased. When the upstream cylinder was free to vibrate, they observed that the front cylinder responded in a similar way to an isolated one and the reduced velocity for the onset of oscillations was now the same as that for the upstream cylinder. At the smallest separations the largest oscillations were observed and three discontinuities appeared, at which the amplitudes decreased suddenly and started to increase again with increasing reduced velocity. They also showed phase differences between the cylinders and how there were preferred phases for the motions, depending on the separation between the cylinders.

To the knowledge of the authors, there is no data for tandem arrangements of cylinders with low mass and damping in which both cylinders are able to vibrate with two degrees of freedom. In this work, the dynamic response and the wake interference of two flexible cylinders with low mass and damping, free to vibrate in any direction, are studied for small separation distances, with no vortex formation in the gap region or showing a bistable regime in which vortices can be formed or not in the gap region depending on what is the effective gap between the cylinders due to their oscillation.

2. Experimental details

The experiments were performed in the water channel at the Department of Aeronautics of Imperial College London. The facility, the models and the set-up are described in detail in Huera-Huarte and Bearman (2009a). The set-up which is shown in Fig. 1, consisted of a supporting structure and a pair of long flexible circular cylinder models. One of the models was instrumented with strain gauges along its length, and this model was always used as the trailing or downstream cylinder (DC). The other one had the same design but strain gauge instrumentation was not embedded in it. The latter, was always placed leading the tandem arrangement as the upstream cylinder (UC). The total length (L) of both cylinder models was 1.5 m and they were made of a 6 mm diameter aluminium core with 15 mm diameter aluminium diaphragms attached to it with cyanoacrylate glue. The diaphragms provided space for the instrumentation cables in the downstream body and maintained a low mass (m) and flexural stiffness (EI). The aluminium skeleton in both models was covered with a transparent flexible PVC skin, yielding external diameters (D) of 16 mm and aspect ratios (L^*), length over diameter, of 93.75. The PVC skin did not allow the water to enter the hollow parts of the models. The UC model was slightly lighter than the DC model because of the absence of instrumentation cables. Its mass per unit length was 0.293 kg/m and its submerged weight w_s was 2.21 N/m. The mass of the instrumented trailing cylinder was 0.362 kg/m and its submerged weight was 2.7 N/m. The mass ratio m^*, defined as the ratio of structural mass to displaced fluid mass ($4m/\rho\pi D^2$), was 1.8 for the DC and 1.3 for the UC, ρ being the density of the fluid. The flexural stiffness was kept very low for both models.