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Wake-induced vibration of tandem and staggered cylinders with two degrees of freedom

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ABSTRACT

The wake-induced vibration (WIV) of two staggered cylinder with two degrees of freedom (2-dof) has been investigated by experiments in a water channel for Reynolds number between 2000 and 25 000. The streamwise separation was fixed to 4 diameters and the lateral separation varied between 0 and 3 diameters for tandem and staggered configurations. Results are presented in the form of trajectories of motion and dynamic response curves of displacements, frequencies and force coefficients. Excitation caused by the WIV mechanism is found to get weaker as the initial position of the downstream cylinder is increased from the centreline of the wake (tandem arrangement) towards the sides. For a lateral separation of 3 diameters wake interference was already found to be negligible. Evidence of a type of wake-stiffness concept is also observed to occur for 2-dof WIV in tandem arrangement, especially for higher reduced velocities. A similar mechanism may also be occurring for staggered arrangements around the centreline.

1. Introduction

The topic of *wake-induced vibration* (WIV) of a pair of interfering cylinders is a fundamental subject in fluid–structure interaction that still draws the attention of many researches. In a few words, WIV is a fluid–elastic mechanism able to excite into oscillatory motion a bluff body immersed in the wake generated from another body positioned upstream. At first sight it appears to be a very simple phenomenon, but careful investigations have uncovered complex mechanisms that can only be understood through the lenses of unsteady fluid–elasticity. In the present study we are concerned with the WIV of the downstream cylinder of a pair arranged in tandem and staggered configurations, i.e. in staggered arrangements the cylinders are not aligned with the flow but offset from the centreline. WIV differs from the well studied phenomenon of *vortex-induced vibration* (VIV)—reviewed by Bearman (1984), Williamson and Govardhan (2004) and others—in the sense that the excitation is not generated in the vortex shedding mechanism of the body itself, but it comes from the interaction of the body with a wake developed further upstream.

It is not difficult to be carried away by the apparent simplicity of the problem and plan or design experiments without considering the number of parameters involved. For example, take two cylinders modelled as rigid bodies with two degrees of freedom (2-dof) each. To start with geometric parameters, there will be two diameters and a streamwise and a cross-flow separation, which will distinguish the tandem from the staggered arrangements. On the structural properties side, there will be different parameters of mass for each cylinder as well as damping and stiffness regarding each direction of motion. After all, a pair of rigid cylinders oscillating in 2-dof will present a dozen of different possible combinations of geometric and

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structural parameters to be considered, not to mention experiments with long flexible cylinders with several modes of vibration. In addition, one may include flow parameters such as speed, velocity profiles and turbulence intensity on the free stream. For this reason, only a few studies that managed to vary one or two parameters at a time were able to contribute to the understanding of the WIV excitation mechanisms and tell it apart from other types of flow-induced vibration of bluff bodies.

Nevertheless, WIV has been revisited by quite a few papers in the recent years. In addition to the papers pointed out along this text, one should refer to the book of Paidoussis et al. (2011) and the comprehensive review paper published by Sumner (2010) as a means to finding old and new literature on the topic of wake interaction. WIV has also been referred to by different names in the past literature, such as 'wake-induced galloping' (Bokaian and Geoola, 1984) and 'wake-displacement excitation' (Zdravkovich, 1988). But we shall follow Assi et al. (2010) and keep the terminology *wake-induced vibration* not to mistake it by 1-dof vibrations normally associated with classical galloping of non-axisymmetric cross-sections.

Bokaian and Geoola (1984) and Assi et al. (2010, 2013) have studied the flow-induced vibration of the downstream cylinder moving only in the cross-flow direction in water channels. Simpson (1977), on the other hand, has investigated the streamwise instabilities of a pair of tandem cylinders in a wind tunnel. Several models have been developed to capture the mechanisms behind this type of flow-induced vibration, most of them starting from quasi-steady assumptions but adding time delays to account for the unsteady effects of the wake–structure interaction (a review of these models is found in Price, 1995). Simpson and Flower (1977) enhanced the quasi-steady model including movements of the upstream cylinder. Tsui and Tsui (1980) further developed an instability analysis for when the cylinders are mechanically coupled. And the nonlinear analysis performed by Price and Abdallah (1990) revealed interesting results about the effect of damping and frequency detuning on the response. Most of these works have been concerned with the vibration of the downstream cylinder undergoing a type of mechanism called 'wake flutter', in which the cylinder is able to extract energy from the flow as it oscillates in an elliptical orbit within the upstream wake. Price (1975), Price and Abdallah (1990) and Naudascher and Rockwell (1994) offer clear descriptions with illustrated explanations of this mechanism.

Fig. 1 presents the velocity field obtained with PIV (particle-image velocimetry) around two static cylinders in staggered arrangements. PIV was performed at mid length to characterise steady wake topology; details on the set-up are presented in Assi (2009). As the downstream cylinder moves away from the centreline, the wake interference from the upstream cylinder is reduced. For the tandem arrangement, in Fig. 1(a), the upstream wake is symmetrically split around the downstream body, while for the staggered configurations in (b) and (c) the upstream wake interferes with the inner side of the second cylinder. Streamlines show that the steady wake of the upstream cylinder is displaced by the presence of the second body. For a lateral separation of $y_0/D = 3.0$ the downstream cylinder appears to be so far out of the upstream wake that its wake symmetry is almost recovered.

We believe Fig. 1 illustrates rather well the phenomenon described by Zdravkovich (2003) as '*wake-displacement*' when he writes that "the downstream cylinder is not *immersed* in the upstream cylinder wake but *displaces* it instead". However, as shown by Assi et al. (2013), the unsteady flow field around a static downstream cylinder is quite different from that around a cylinder that is not moving across the wake. In fact, the unsteady wake interference was found to be fundamental to excite WIV. Assi et al. (2010) showed how the instantaneous vortex interference may enhance or diminish lift depending on the wake pattern. Hence the time-averaged flow fields in Fig. 1 are very limited in terms of information they provide for an investigation of the unsteady phenomenon. Nevertheless, they show how far out of the centreline the downstream cylinder needs to be in order for wake interference to become insignificant, setting the boundaries for the present study.

2. Method

The present paper is a follow-up on the previous works of Assi et al. (2010, 2013) so, in order to avoid unnecessary lengthy repetition, the reader will be constantly referred to those papers. In those previous works we kept constant as many parameters as possible in order to investigate the intricate mechanisms of wake interference. Only allowing for the downstream cylinder of a tandem pair to respond to flow excitation in the cross-flow direction made it possible to identify the complex unsteady excitation mechanism by vortex–structure interaction and the powerful concept of wake stiffness. Now, in the present study, we shall release some constraints adding new parameters to the investigation.

The basic arrangement is illustrated in Fig. 2. The initial position of the downstream cylinder can be varied from the tandem arrangement (in which both cylinders are aligned with the flow direction) to staggered configurations changing the lateral spacing between the bodies, hence x_0 and y_0 define the initial geometry of the pair. The streamwise separation, measured from centre to centre, was kept fixed at $x_0/D = 4.0$ at all times and y_0/D was varied between 0 and 3. The upstream cylinder was always static while the downstream cylinder was allowed to respond with oscillations in 2-dof in the cross-flow (y) and streamwise (x) directions. Although this represents only a sample of the multi-parametric universe, by testing the system on these conditions we may identify some general characteristic behaviours. For example, we will be able to notice the decreasing effect of the WIV mechanism as the downstream cylinder moves away from the centreline of the wake and we will see evidence for the existence of 'wake-stiffness' for configurations other than the tandem arrangement (to be described later).

Fig. 3, reproduced from Assi et al. (2010), presents the WIV response of the downstream cylinder of a tandem pair free to respond in one degree of freedom (1-dof) in the cross-flow direction. The top graph shows the variation of the amplitude of