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Vortex-induced vibrations of cylinders bent by the flow

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Flexible cylinders exposed to transverse flows may undergo transverse vortex-induced vibrations due to the oscillating lift force imposed by their wake. But the drag on such structures often leads to large in-line deflections that may significantly affect the dynamics through the combined effects of the curvature-induced tension, the local inclination of the cylinder, the non-uniformity of the normal flow profile, and the large axial flow component. In this paper, we investigate the consequences of flow-induced bending on the vortex-induced dynamics of slender cantilever cylinders, by means of numerical simulations. We combine a distributed wake oscillator approach to model the dynamics of the wake with Lighthill's large-amplitude elongated body theory to account for the effect of the axial flow in the reactive (added mass) force. The use of such reduced order models facilitates the identification of the physical mechanisms at play, including through the linear analysis of the coupled fluid–structure system. We find that the primary consequence of flow-induced bending is the inhibition of single mode lock-in, replaced by a multi-frequency response of the structure, and the reduction of the vibration amplitude, as a result of the broadening of the wake excitation spectrum and of the localization of the energy transfer due to the variations induced in the normal flow profile. We also find that the curvature-induced tension is of negligible influence, but that the axial flow component may on the other hand significantly alter the dynamics owing to the destabilizing effect of the reactive force on the structural modes.

1. Introduction

The vortex-induced vibrations (VIVs) of slender cylindrical structures has been a prominent subject of research for many years. Originally, a better understanding of this phenomenon was sought in the civil and marine engineering community mostly because of the damage it may cause on a number of flow-exposed structures such as buildings, power transmission lines, marine risers, towing cables, or mooring lines. For extensive reviews regarding VIVs, the reader is referred to Williamson and Govardhan (2004), Sarpkaya (2004), Williamson and Govardhan (2008), Bearman (2011) and Wu et al. (2012). More recently, a renewed interest for the VIVs has arisen from the potential they bear as an alternative source of energy (Bernitsas et al., 2008).

The large majority of existing studies focus on the VIVs of straight cylinders in a variety of configurations: rigid or flexible, perpendicular to the flow or slanted, exposed to a uniform or a sheared flow. However, most of the off-shore flexible structures such as those cited above are actually greatly deformed in the direction of the flow under the effect of the free-stream. This configuration differs from the case of a straight cylinder on several aspects. First, the deflection in the plane of the free-stream of a cylinder is responsible for a curvature-induced tension inside the structure. The tensioning

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of the cylinder may affect its natural frequencies, and consequently its dynamic response to the wake excitation. Secondly, deflected structures are not locally perpendicular to the flow, which modifies the features of vortex shedding in the wake and the associated forces on the structure. Besides, a curved structure experiences a spanwise variation of its angle with the free-stream. Finally, the reconfiguration of the structure leads to a large axial component of the flow on the most inclined portion of the structure that may even become dominant when the deflection is significant. The consequences of some of these specificities have been individually studied, see for instance Srinil et al. (2009) and Srinil (2010) for the structural effect of the curvature, Lucor and Karniadakis (2003), Facchinetti et al. (2004b), Franzini et al. (2009), Jain and Modarres-Sadeghi (2013) and Bourguet et al. (2015) for the effect of the inclination, or Vandiver (1993), Chaplin et al. (2005), Trim et al. (2005), Lucor et al. (2006), Violette et al. (2010) and Bourguet et al. (2013) for the effect of non-uniform normal flow profiles, but their combined effects may lead to a significant alteration of the wake–structure interaction that has not yet been fully investigated.

As a first step towards the understanding of VIVs of bent cylinders, Miliou et al. (2007) and de Vecchi et al. (2008) numerically explored the vortex shedding process in the wake of a rigid cylinder in the shape of a convex or concave quarter of a ring, when the structure is respectively fixed or forced into an oscillatory motion. Building on these results, Assi et al. (2014) and Seyed-Aghazadeh et al. (2015) experimentally investigated the free vibrations of similar structures and found that the amplitude of the oscillations is much reduced compared to the straight configuration. Two studies provided experimental observations regarding the VIVs of flexible structures about a curvy shape: the experimental work of Zhu et al. (2016) considered the vibrations of a naturally concave-shaped cylinder subjected to a shear flow, while that of Morooka and Tsukada (2013) tested a model riser deformed in the shape of a concave catenary under the effect of a uniform free-stream. Finally, Bourguet et al. (2012, 2015) numerically investigated the VIVs of tensioned flexible beams respectively exposed to a normal sheared flow and an inclined uniform flow. Both studies considered the influence of a small average in-line deformation and noted the transition from a mono-frequency to a multi-frequency response associated with a modification of the normal flow profile due to the bending. A reduction of the amplitude of the VIVs was also reported in Bourguet et al. (2015). At this point however, a theoretical study is still missing to clarify the consequences of flow-induced bending on the VIVs of slender cylinders in large deformations and identify the physical mechanisms at play. One may for instance wonder how the bending-induced shear in the normal flow might impact the vibration spectrum, whether lock-in may or may not still occur, or furthermore how the amplitude of vibration might be affected?

But the flow-induced bending of the structure may have even more dramatic consequences. Indeed, slender structures in axial flows are liable to a flutter instability (Datta and Gottenberg, 1975; Yadykin et al., 2001; Païdoussis et al., 2002; Semler et al., 2002). This self-induced dynamics results from the destabilizing effect of the inviscid pressure forces associated with the deformation of the structure in a free-stream with a significant axial component (Eloy et al., 2007; Singh et al., 2012a). When a cylinder deflects in a transverse flow, the increasing spanwise component of the free-stream may thus be the cause of such instability. More generally, the influence of the inviscid pressure forces on the structural modes may have consequences on the vortex-induced dynamics even in a domain of the parameter space where the system does not flutter.

The purpose of the present paper is to provide an analysis of the small-amplitude vibrations of slender cylinders bent by the flow by means of reduced order models to identify the physical mechanisms at play. In particular, a formulation of the inviscid pressure forces based on Lighthill's large-amplitude elongated body theory (Lighthill, 1971) will be used to account for the destabilizing effect of the axial component of the free-stream. We will also make use of a wake oscillator to describe the lift resulting from vortex shedding. This class of models was originally derived to represent the dynamics of the free wake behind a fixed structure (Birkhoff and Zarantonello, 1957; Bishop and Hassan, 1964), and they have been proved able to capture some characteristic features of the vortex shedding mechanism, such as the formation of cells in shear flow (Noack et al., 1991; Mathelin and de Langre, 2005). Such models have also been proved useful in qualitatively describing the physics of VIVs when coupled with a structural oscillator (Hartlen and Currie, 1970; Skop and Balasubramanian, 1997; Balasubramanian et al., 2000; Mukundan et al., 2009; Srinil and Zanganeh, 2012), and they have been validated against experimental and numerical results (Violette et al., 2007). In this regard, the work of Facchinetti et al. (2004a) demonstrated that features such as the boundaries of the lock-in range, the amplitude of the vibrations or the phase between the structure and the wake are correctly predicted when a coupling term proportional to the structural acceleration is used. The subsequent work of de Langre (2006) and Violette et al. (2010) further demonstrated that many features of the nonlinear limit-cycle dynamics can be interpreted through the linear analysis of the coupled wake–structure oscillators.

In Section 2, the model for the flow–structure interactions and its specific adaptations to the problem in question are detailed. The consequences of the flow-induced bending on the VIVs are then discussed in Section 3 based on the results of numerical simulations.

2. Model

2.1. Theoretical modelling

We consider the model system represented on Fig. 1. A circular cylinder of length L, diameter D and mass per unit length m is clamped perpendicular to a uniform and steady flow of velocity $U\boldsymbol{e_x}$ of a fluid of density ρ. We assume the cylinder is slender ($D \ll L$) and we model it as an inextensible Euler–Bernoulli beam of bending stiffness EI (see more details about the structural model in Appendix A.1). We note s the curvilinear coordinate along the span from the clamped end to the free