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Computational study of vortex-induced vibration of a sprung rigid circular cylinder with a strongly nonlinear internal attachment

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ABSTRACT

For a Reynolds number (Re) based on cylinder diameter of 100, and a ratio of cylinder density to fluid density of 10, we investigate the effect of a strongly nonlinear internal attachment on the vortex-induced vibration (VIV) of a rigid circular cylinder restrained by a linear spring, and constrained to move perpendicularly to the mean flow. The variational multiscale residual-based stabilized finite-element method used to compute approximate solutions of the incompressible Navier–Stokes equations about the moving cylinder is coupled to a simple model of a "nonlinear energy sink" (NES), an essentially nonlinear oscillator consisting of a mass, a linear damper, and a strongly nonlinear spring. The NES promotes nearly one-way transfer of energy to itself from the primary structure (the cylinder), resulting in reduction of the amplitude of the limit-cycle oscillation by as much as 75%, depending on the parameters characterizing the NES. Various mechanisms of nonlinear interaction of the NES with the cylinder undergoing VIV are discussed. Although no optimization of the NES is performed in this work, we demonstrate capacity for passive suppression of VIV and compare the performance of the NES to the tuned linear absorber of equal mass.

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1. Introduction

The geometrically simplest case of bluff-body vortex-induced vibration (VIV) involves "cross-flow" past a circular cylinder. At sufficiently small values of the Reynolds number $\mathrm{Re}=U_0D/\nu$, where U_0 is the free-stream speed, D is the cylinder diameter, and ν is the kinematic viscosity, the flow past a fixed rigid cylinder is steady, two-dimensional, and symmetric about the diametral plane parallel to the mean flow, with no lift force perpendicular to the direction of the mean flow. Beyond about Re=46, the flow becomes time-periodic and a series of alternating vortices is observed in the wake, leading to a time-periodic lift force. The flow remains two-dimensional up to about Re=175, beyond which a spanwise periodicity appears. At still higher Re, the flow becomes temporally chaotic and ultimately turbulent.

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When the cylinder is not held fixed, the time-dependent lift force associated with the shedding of alternating vortices leads to VIV, as reviewed by Bearman (1984), and more recently by Sarpkaya (2004), Williamson and Govardhan (2004), and Bearman (2011). In those cases where VIV is undesirable, both active (Skaugset and Larsen, 2003) and passive (Assi et al., 2010; Bernitsas and Raghavan, 2008; Dong et al., 2008; Owen et al., 2001) approaches to its suppression have been considered. To date, the active approaches either suffer from what, in applications, would be excessive power requirements, or require suction and blowing, involving internal "plumbing" within the cylinder. To date, all passive design approaches involve addition of appendages (e.g., shrouds, helical appendages, freely rotating plates) to the cylindrical geometric boundary between the fluid and structure. These appendages can increase or decrease the drag, and can also lead to structural issues of their own.

In this work, we discuss the dynamics of vortex-induced vibration of a sprung cylinder with an internal strongly nonlinear attachment, and demonstrate the capacity of the internal nonlinear attachment for passive VIV suppression. This approach, known as "targeted energy transfer" (TET) (Vakakis et al., 2008), involves attaching an essentially nonlinear element (a "nonlinear energy sink," or NES) to a primary structure in order to promote nearly one-way transfer of energy from the latter. By "essential nonlinearity" we connote a nonlinear force-response characteristic that lacks a linear part, so the resulting dynamics cannot be linearized. The only previous application of TET to suppress limit-cycle oscillations is the work of Lee et al. (2007a, 2007b) and Gendelman et al. (2010) in the context of a rigid wing in subsonic flow. For a 2-DOF model of a generic transport airfoil in a simple model of subsonic flow, Gendelman et al. (2010) showed that aeroelastic flutter, at speeds significantly in excess of the nominal critical flutter speed, could be greatly suppressed or completely eliminated by a single-DOF NES.

In conformance with what would seem to be the simplest implementation for hollow-cylinder applications, we consider the case in which the NES (consisting of a mass, a linear damper, and a strongly nonlinear spring) is located within the interior of the cylindrical domain whose outer boundary is in contact with the flow. In this case, the only way in which the NES can affect the flow and possibly suppress vortex-induced vibration is through its alteration of the rigid-body motion of the cylindrical boundary.

While there are key differences (Anagnostopoulos and Bearman, 1992) between VIV in the laminar regime and the turbulent regime of greater interest to applications, the flow that we consider, at $Re=100$, is of interest for three main reasons. First, the $Re=100$ flow past a rigid circular cylinder restrained by a linear spring, and constrained to move perpendicularly to the mean flow, has become a very popular testbed for investigating free response in VIV. Beyond the reviews cited above, recent work at $Re=100$ includes the discovery by Singh and Mittal (2005) of a hysteretic jump at the high-Re end of the lock-in region, a study of blockage effects by Prasanth and Mittal (2008), and additional studies by Prasanth and Mittal (2009), Placzek et al. (2009), and Bahmani and Akbari (2010). Second, the flow at this Re is laminar and two-dimensional, and hence can be readily simulated in order to perform detailed parametric studies without concern for issues such as unresolved scales and the attendant unmodeled dynamics associated with simulations of three-dimensional turbulent flow. Third, as shown by Roshko (1954), one of the notable features of the flow past a fixed cylinder is that the Strouhal number $St=f_sD/U_0$ (a dimensionless shedding frequency, where f_s is a properly defined dimensional shedding frequency) maintains a nearly constant value ($St=0.19\pm0.02$) over $10^2\leq Re\leq 10^4$, i.e., from the laminar two-dimensional regime well into the turbulent regime. As discussed by Roshko (1954) and Williamson (1996), significant aspects of vortex shedding by a cylinder are qualitatively similar over wide ranges of Re, including at least part of the laminar regime. Thus, there is some reason to believe that methods that suppress VIV at $Re=100$ will be useful, or can be adapted for use, at much higher Re. The main focus of this work is to study VIV of a sprung cylinder with a strongly nonlinear attachment, a problem that to the authors' best knowledge has not been addressed previously in the literature. No formal optimization of the nonlinear attachment is carried out, although we demonstrate the capacity of this approach for passive VIV suppression, and compare its performance to the tuned linear absorber with equal mass. (We note that even this latter problem has not been addressed for cylinder VIV in the literature.)

The remainder of the paper is organized as follows. In Section 2, we provide a brief description of the finite-element formulation used to compute approximate solutions of the two-dimensional incompressible Navier–Stokes equations. Validation of the computational approach, including comparison to previous free-response VIV studies, is provided in Section 3. The effects of our TET approach on the dynamics of VIV, and on passive suppression of VIV, are presented in Section 4. The emphasis is on how the dynamics and degree of suppression depend on the NES parameters, and on the similarity between suppression mechanisms in this first application of TET to an infinite-dimensional system, and those found in previous work on finite-dimensional systems. Some conclusions are presented in Section 5.

2. Formulation and computational approach

2.1. Physical model and governing equations

In this section we specify the elements of the physical model (viscous flow past a two-dimensional circular cylindrical boundary containing a nonlinear energy sink), and show how they are coupled together as a dynamical system.

Fluid dynamics. We consider two-dimensional flow past a circular cylinder of diameter D, with steady and uniform upstream velocity $U_0\mathbf{e}_x$. We take the flow to be governed by the Navier–Stokes equations for a constant-density,

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