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Active flow control of vortex induced vibrations of a circular cylinder subjected to non-harmonic forcing

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ABSTRACT

A wide variety of waves and currents are abound in wind and ocean engineering practice. These wave forms could be harmonic as well as non-harmonic and may lead to the formation of wake vortices, behind a circular cylinder. The alternating lift forces on such structures could in turn result in damaging flow induced vibrations. In the present study, we propose a simple momentum injection based active flow control strategy to suppress such vortex induced oscillations at low Reynolds numbers. Two small control cylinders located at 120°, behind the main cylinder play the role of actuators, that enforce the desired momentum injection. Detailed Computational Fluid Dynamics (CFD) simulations are carried out, by solving mass, momentum conservation equations in conjunction with a control equation, and a dynamical evolution equation for the structural motion. Non-harmonic inlet forcing on a flexibly mounted circular cylinder generates vortex induced vibrations, which is numerically simulated. Then by controlling the wake vortices, vortex induced vibrations are completely controlled. Analysis of the leeward region behind the main cylinder reveals a different wake signature, with blobs of residual vorticity along the wake centreline. This is attributed to the phase asynchrony between the inlet forcing and the vortex induced vibrations.

1. Introduction

In wind and ocean engineering practice, waves are often viewed as an eternal problem. They possess a variety of characteristics, with diverse features and implications. They may appear to be regular or irregular, linear or non-linear, unidirectional or omnidirectional etc. These waves propagate under the influence of gravity, surface shear generated by the wind on the interface, bed friction at the bottom, salinity gradients, temperature gradients etc. When these ocean waves encounter an offshore structure, they develop oscillatory fluid forces, resulting in fatigue induced failure. Most submerged ocean structures such as, runners, risers, spars, Tension leg platforms (TLP)'s etc, are essentially circular in their basic configuration. Due to wide range of applications, with various levels of idealizations, there is plethora of literature on experimental, numerical and theoretical investigations. Several studies have focussed on the hydrodynamics of flow past circular structures and their resulting vortex induced vibrations (VIV) (Sarpakaya, 2010; Chakrabarti, 2002; Sumer and Fredsoe, 1997). Design of structures that include detailed fluid structure interaction effects is indeed complex. Seminal contributions of Sarpakaya (2010) and Chakrabarti (2002) etc have given the impetus for the development of theoretical frame work into practical use, by combining wave theories with force predictions such as, drag, lift, inertial forces, coupled to structural resistance.

2. Background literature

The literature on vortex shedding and the associated flow induced vibrations is indeed vast, owing to a wide variety of engineering applications. This section gives a brief overview of experimental and numerical studies involving steady and oscillatory flows and the control strategies typically adapted in the literature.

2.1. Vortex shedding and the induced vibrations

A wide range of ocean engineering structures need to be designed to cater to a spectrum of functionalities. Most of these configurations of practical interest can be visualized through the problem of model flow past a circular cylinder. In fact, there is abundant literature on several aspects of uniform flow past bluff bodies, in particular the analysis of

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wake and the associated vortex dynamics (Zdravkovich, 1997; Williamson, 1996). However, in wind and ocean engineering settings, the flow physics is modified by complex features such as, oscillatory flow field, wind shear on the surface, waves, currents etc. Hence, fluid flow analysis covering harmonic and non-harmonic forcing is highly desirable. It is well known that, when the natural frequency of the offshore structure is in the neighbourhood of vortex shedding frequency, it could result in *phase lock-in* or *synchronization*. This could be detrimental to a number of applications such as, mooring cables, catenary risers, offshore platforms, wind turbine sub-structures etc (Chakrabarti, 2002). The cyclic loads may cause large amplitude of oscillations, which lead to resonance and trigger failure. Hence, detailed analysis of flow induced vibrations (FIV) suppression techniques for oscillatory field conditions is of utmost importance in the design of offshore structures.

Detailed experimental studies on vortex shedding and vortex induced vibrations (VIV) are well documented in books such as Sumer and Fredsoe (1997) and Zdravkovich (1997), as well as in review papers of Williamson and Govardhan (see Williamson and Govardhan, (2004) and (Williamson and Govardhan (2008)). Since the experimental studies are both specific and extensive, we review only the numerical simulations, related to VIV. The real interest is always in the life time prediction of different structures due to fatigue. To this end, it is important to develop numerical simulations, which are accurate and reliable. Hence, investigators have focused on the development of numerical solvers, validation studies, turbulence models, etc. Wanderley and Levi (2002) and Wanderley and Levi (2005), have employed Beam-Warming based implicit schemes for the Navier-Stokes simulations with a zero equation Baldwin-Lomax model for the turbulence closure. In the vicinity of the synchronization regime, they have reported good predictions in capturing the upper branch of the amplitudes of oscillation against the well known experimental study of Khalak and Williamson (1997). Their VIV simulations cover low mass-damping parameters in the low Reynolds number range, where the cylinder is spring supported, with vibrations enabled only in the transverse direction. In the other works of Wanderley and Soares (2015) and Wanderley et al. (2008), Unsteady Reynolds-Averaged Navier-Stokes equations (URANS) in curvilinear coordinates were used in conjunction with an upwind type Total Variation Diminishing (TVD) conservative scheme and a k-ϵ turbulence model. The cylinder response amplitude, phase angles, response frequency, and lift forces were obtained in the reduced velocity range of 2–12, for six different fixed Reynolds numbers. The group of Zhao et al. (2012, 2013), Yang et al. (2013) and Zhao (2013) have extensively studied the VIV phenomena of flexible cylinders subjected to oscillatory flows, with the aid of Petrov-Galerkin based Finite Element Method(FEM) in conjunction with an Arbitrary Lagrangian Eulerian(ALE) scheme. A similar stabilized FEM based scheme, known as streamline upwind Petrov-Galerkin (SUPG) technique was employed by Singh and Biswas (2013) to simulate the phenomenon of VIV past a square cylinder.

2.2. Oscillatory flows and their influence

An oscillatory flow (a simple sinusoid) past a circular cylinder, is a function of the Keulegan-Carpenter number (KC) and Reynolds number (Re). It is well known that these two non-dimensional groups (Re and KC)are linearly related through the viscous parameter (β), as (Re=KC*β). In the ocean environment, the oscillatory waves and currents occur in all forms and sizes, which are neither exactly periodic nor completely aperiodic. Furthermore, they may or may not propagate in the same direction. However, these oscillatory, linear or non-linear wave forms are an important precursor to study the coupled fluid structure interaction problems. The influence of oscillating flow past a cylindrical structure, has received a lot of attention through analytical, numerical and experimental means (Sarpakaya, 1986; Justesen, 1991; Qamar et al., 2001; Bearman et al., 1985; Obasaju et al., 1988; Badr, 1994; Badr et al., 1995; An et al., 2009; Konstantinidis and Bouris, 2010, 2009). The wake dynamics and forces are substantially effected due to the amplitude and frequency of the incoming oscillatory flow. Determination of hydrodynamic force coefficients, i.e. drag, lift and side forces, is indeed central to the design of offshore structures.

In the literature, the dynamics of the circular cylinder wake is analyzed by fixing suitable values for the Kulegen- Carpenter (KC) and Reynolds number (Re). A number of detailed oscillatory flow measurements past a circular configuration were compiled in Sumer and Fredsoe (1997). Badr (1994) investigated oscillating inviscid flow over an elliptic cylinder for various angles of attack. For an axis ratio of 1.0, an elliptic cylinder is indeed a circular configuration. Badr (1994) obtained hydrodynamic force coefficients for different axis ratios. Badr et al. (1995) have numerically integrated the unsteady N-S equations to investigate the influence of viscous fluid oscillating in a direction normal to the circular cylinder. The use of boundary layer coordinates have enabled a higher order accuracy, which is particularly suited for high Reynolds number flows. An et al. (2009) have performed finite element (FE) based calculations to investigate the oscillatory effects, in the range of $2 \leq KC \leq 40$. For this KC range, authors have justified the use of a 2-D FE calculations in conjunction with a $k - \omega$ turbulence model, stating three dimensional effects are rather weak.

Zhao et al. (2012) have investigated the VIV response of an elastically mounted cylinder in an oscillatory flow in the reduced velocity (V_r) range of 1–36, and KC range of 10 and 20. Zhao et al. (2011) have numerically investigated the influence of sinusoidal oscillatory flow at an oblique angle of attack on a circular cylinder. Recently, Yang et al. (2013) have analyzed, how the presence of a piggy back cylinder influences the vortical structures behind the main cylinder for different gaps and orientations facing an oscillatory upstream flow. They have confirmed the key role of the piggyback cylinder, in inducing the pressure field of its own and in attracting the vortices shed by the main structure. Al-Jamal and Dalton (2013) have numerically simulated the sinusoidal oscillatory flow inline with an imposed uniform flow. The flow field in the vicinity of the cylinder surface was found to be some what unpredictable, when compared to purely wavy flow. Hence, the need for simultaneously accounting for the interactions, when analyzing such flows. The mushroom-type structures in the vicinity of a cylinder was analyzed by Suthon and Dalton (2011), which is a manifestation of the Honji instability.

Of late, the control of vortex induced vibrations has gained prominence in energy-harvesting applications, to enable the exploitation of abundant hydro-kinetic energy present in rivers and water streams (Dhanwani et al., 2013). Raghavan and Bernitsas (2011), Chang et al. (2011) and his co-workers have performed detailed work and demonstrated the energy extraction technology. The integration of active flow control strategies would certainly accrue immense benefits as VIV can be controlled for suppression or enhancement. Since the ocean waves and currents can be approximated as either harmonic or non-harmonic. In this regard, the studies of Konstantinidis and Bouris (2009) and Konstantinidis and Bouris (2010) are worth mentioning. These investigations have opened up new control possibilities by adjusting the waveform of the forcing drivers. Here, the vortex formation modes of the circular cylinder wake and the fluid loading on the cylinder were found to be sensitive to non-harmonic forcing even though the waveform was of the same period and amplitude.

2.3. Passive and active control of VIV

Vortex induced oscillations can be suppressed by different means either by making modifications to the geometry of the structure or by effecting fluid dynamic changes. It is certainly important to avoid the vicinity of the natural frequency by varying the structural stiffness or damping, as the vortex shedding frequency can easily be locked-in. However, for reasons of cost and optimal design considerations, it is not always feasible to comply with it. Hence, a number of passive