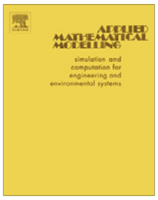
Applied Mathematical Modelling 37 (2013) 284–307

Contents lists available at SciVerse ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm



Numerical simulation of vortex induced vibrations and its control by suction and blowing

K. Muralidharan, Sridhar Muddada, B.S.V. Patnaik *

Fluid Mechanics Laboratory, Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai 600 036, India

ARTICLE INFO

Article history:
Received 21 August 2011
Received in revised form 21 November 2011
Accepted 15 February 2012
Available online 3 March 2012

Keywords:
Active flow control
Flow induced vibrations
Fluid structure interaction
CFD

ABSTRACT

The vortex formation and shedding behind bluff structures is influenced by fluid flow parameters such as, Reynolds number, surface roughness, turbulence level, etc. and structural parameters such as, mass ratio, frequency ratio, damping ratio, etc. When a structure is flexibly mounted, the Kármán vortex street formed behind the structure gives rise to vortex induced oscillations. The control of these flow induced vibrations is of paramount practical importance for a wide range of designs. An analysis of flow patterns behind these structures would enable better understanding of wake properties and their control. In the present study, flow past a smooth circular cylinder is numerically simulated by coupling the mass, momentum conservation equations along with a dynamical evolution equation for the structure. An active flow control strategy based on zero net mass injection is designed and implemented to assess its efficacy. A three actuator system in the form of suction and blowing slots are positioned on the cylinder surface. A single blowing slot is located on the leeward side of the cylinder, while two suction slots are positioned at an angle $\alpha = 100^\circ$. This system is found to effectively annihilate the vortex induced oscillations, when the quantum of actuations is about three times the free stream velocity. The dynamic adaptability of the proposed control strategy and its ability to suppress vortex induced oscillations is verified. The exact quantum of actuation involved in wake control is achieved by integrating a control equation to decide the actuator response in the form of a closed loop feed back system. Simulations are extended to high Reynolds number flows by employing eddy viscosity based turbulence models. The three actuator system is found to effectively suppress vortex induced oscillations.

1. Introduction

Fluid flow past a circular cylinder is a model problem of fundamental interest, as it impacts a number of practical engineering applications. Vortices are formed and shed behind bluff bodies causing a sinuous wake in its downstream. Alternating eddies formed behind a bluff object gives rise to fluctuating lift and drag forces. Hence, the problem of flow past a circular cylinder and its wake control is of interest to a variety of design practitioners who are affected by vortex induced oscillations such as, bridges, skyscrapers, offshore structures, marine cables, submarines, etc. [1].

The fluctuating force field exerted by the fluid on the structure, causes it to deform if rigidly mounted or oscillate if it is flexibly mounted. When the structure oscillates or undergoes deformations, its orientation to the flow and in turn, the fluid forces acting on it changes. The governing equations for such a system are, the mass and momentum conservation for the

---

* Corresponding author.
E-mail address: bsvp@iitm.ac.in (B.S.V. Patnaik).

0307-904X/$ - see front matter © 2012 Elsevier Inc. All rights reserved.
doi:10.1016/j.apm.2012.02.028

fluid, and an additional equation that would describe the dynamical motion of the structure. Thus the study of vortex induced vibration (VIV) involves a two way coupling between the dynamical equations that govern both the fluid and the structure [2]. A number of recent and critically acclaimed reviews on diverse aspects of flow induced oscillations are available in the literature (see references [3–5]).

The problem of flow past vibrating bodies can be tackled in two fundamentally different ways, which perhaps complement each other. The first approach is the study of forced vibrations, where an external excitation is imparted to the rigid body and then its effect on the flow field is investigated [6–8]. Here, the frequency and amplitude combination for the oscillations can be chosen at will and imposed on the circular cylinder, to study the effect of an oscillating bluff body in a fluid stream. The second approach involves study of free vibrations, where the fluctuating temporal lift force induces the body to oscillate. This would generate the necessary coupling between the structure and the flow field, to result in the evolution of cylinder displacements.

Feng [9] contributed to some of the landmark experimental measurements of structural response for an elastically mounted cylinder. He measured quantities such as, amplitude of cylinder vibration (y), vibration frequency (f_v) and phase difference (ϕ) between force and displacement, etc. These quantities were plotted against normalized velocity ($v_r = u/f_nD$). Two distinct amplitude branches, namely the 'initial' branch and the 'lower' branch, were observed with a jump in response amplitude, with a significant jump in the phase of the pressure fluctuations relative to body motion. A jump in phase angle between transverse force and displacement under resonance, is typically matched by a switch in the timing of vortex shedding. Williamson and Roshko [8] have associated this jump to a shift from $2S$ vortex shedding mode to $2P$ mode. Here $2S$ refers to shedding of two alternating eddies, while $2P$ refers to two pairs of eddies being shed on each side of the cylinder. Anagnostopoulos and Bearman [10] have performed 1-DOF experiments and captured the *lock-in* range and the phenomenon of beating for pure laminar vortex shedding range $Re \approx 90 - 150$. One of the first successful attempts to numerically simulate flow past a vibrating body has employed Marker and cell (MAC) method [11]. Chilukuri [12] has improved the predictions of Hurlbut et al. [11] by using simplified MAC approach (SMAC). Patnaik et al. [13] have used Galerkin based finite element method to capture the synchronization regime and associated wake patterns. Meneghini and Bearman [14] have used a discrete vortex method (DVM) with a vortex in cell (VIC) procedure by incorparating viscous diffusion. They have demonstrated that $2S$ mode persists up to $A/D = 0.6$ and beyond which $P + S$ type wake pattern was found to prevail. Zhou et al. [15] have analyzed the cylinder response, damping, forces induced, etc. employing discrete vortex simulations. Leontini et al. [16] have performed experiments to determine if forced oscillations were consistent with self excited oscillations. Although similarities were seen, considerable sensitivity to input forcing was noticed. Khalak and Williamson [17] carried out free vibration studies with low mass damping and obtained a response pattern markedly different from Feng's [9] findings. Among the analytical approaches, Bishop and Hassan [7] were the first to model vortex shedding as a non-linear fluid oscillator and coupled it to the structural oscillator.

The rapid advances in materials, is making the structures more flexible and lighter, this necessitates analysis of vortex induced vibrations. Therefore the ability to manipulate and control the flow field to reduce flow induced oscillations is gaining importance. Control of these vibrations can be attained by modifying the fluid forces responsible for oscillation, either through active or passive means. Active closed loop control naturally lends itself to feedback mechanism and changes in upstream conditions. However, passive strategies such as helical strakes, shrouds, slats, splitter plates, etc. do not require additional energy expenditure [18]. A wide variety of other active and passive control strategies have been reported in the literature [19]. Recently, Baek and Karniadakis [20] have introduced a slit along the streamwise direction, which passes through the cylinder to create a jet that interacts with the wake to suppress vortex shedding. Chen and Aubry [21] have developed a closed loop algorithm to suppress vortex induced vibrations by means of direct numerical simulations (DNS). They have used Lorentz forces to control the cylinder oscillations based on partial flow information available on the surface of the cylinder. However, in practical applications, blowing and suction [22], accoustic acutations [23] and cylinder rotations [24] are some of the widely known active flow control techniques. Inspired by the pioneering work on chaos control by OGY [25], Patnaik and Wei [26] have proposed the stabilization of unstable periodic orbits (UPO) through synchronization based coupling between driver system and target system. By this coupling, complete annihilation of wake vortices behind a D-cylinder was achieved. The strategy of momentum injection control was further extended by Muddada and Patnaik [27] to control vortex shedding behind a circular cylinder by means of two symmetric rotating elements.

Although some of the attempts mentioned above, are only theoretical in nature, the need to control VIV is of concern to practicing engineers. In the present study, we investigate the influence of vortex induced vibrations on the Kármán vortex street, and the resulting modifications on the wake zone. To start with, the self excited nature of the oscillations are allowed to be generated. We then, investigate the influence of suction and blowing in controlling these self-excited oscillations. To this end, the following objectives have been framed:

- To validate the influence of forced cylinder oscillations on the vortex structures behind a circular cylinder by generating different wake modes such as $2S$, $2P$, and $P + S$ for different excitation frequency and amplitude combinations.
- To investigate free vibrations by coupling equation of structure with the equations governing the fluid flow.
- To study the response of the circular structure under the active flow control strategy of suction and blowing. Further more, to investigate the efficacy and dynamic adaptability of suction and blowing on the self excited oscillations.
- To study the effectiveness of blowing and suction for high Reynolds number turbulent wakes.