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Modification of response and suppression of vortex-shedding in vortex-induced vibrations of an elliptic cylinder

Deepak Kumar, Manik Mittal, Subhankar Sen*

Department of Mechanical Engineering, Indian Institute of Technology (ISM) Dhanbad, Dhanbad 826004, India

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ABSTRACT

Numerical experiments are performed at a Reynolds number, *Re* of 100 to explore in two-dimensions, the undamped, transverse-only vortex-induced vibrations of a rigid elliptic cylinder of aspect ratio 0.5. With major axis oriented parallel to the flow, the cylinder behaves as a streamlined object. The mass ratio of the oscillator is 10. *Re* is based on the length of the major axis. The reduced speed, U^* is varied from 1 to 8. The lock-in initiates at $U^* = 3.5$ and is soft in nature. The extent of lock-in gets severely truncated as compared to the one for a bluff oscillator; it spans just over an extremely narrow U^* range of 3.5 to 4.2. The onset and closure of lock-in are marked with the oscillation frequency attaining its maximum and minimum, respectively. Streamlining of oscillator eliminates the whole of initial, quasi-periodic lower and desynchronization components of response. The response consists of a fragile periodic lower branch stretching over the range of lock-in and bracketed by a dominant pair of steady state regimes. The occurrence of peak response is noted at the onset of lock-in and the peak value is about 0.06 times the length of major axis. A closed standing wake characterizes the steady regimes while periodic vortex-shedding relates to the lower branch with weak vibrations. Interestingly, even in the steady regimes, the reduced speed is found to influence the surface pressure whereas global quantities like drag and lift forces remain invariant. In the lower branch, the mean surface pressure exhibits symmetry about base, thus mean lift disappears and wake mode is the basic anti-symmetric 2S. At the onset of lock-in, the instantaneous surface pressure is noticeably asymmetric along the upper and lower surfaces. Thus, vortex-shedding is strong and r.m.s. lift high. With rising U^*, the strength of shedding decays, asymmetry of instantaneous pressure about the base weakens and consequently, r.m.s. lift falls. At $U^* = 4.3$, the free shear layers turn straight, shedding gets suppressed and the regime of steady state recovers.

1. Introduction

The study of flow-induced vibrations (FIV) of a rigid obstacle in a moving viscous fluid is of vast engineering significance in several mechanical, civil and offshore applications. The free or vortex-induced vibration (VIV) of an oscillator is a kind of FIV where the oscillation amplitude is of self-limiting nature and a mutual feedback continues to exist between the oscillator and flow. Thus, VIV involves a coupling of the motion of fluid and solid media. This coupling is due to time-dependent no-slip condition as well as vortex-induced fluid loading at the fluid-solid interface. VIV is studied experimentally as well as numerically, i.e. by direct numerical simulation of the flow and rigid body equations. Depending on whether the flow/oscillator equations are solved simultaneously or separately, numerical approach is further classified as monolithic and staggered, respectively. The stabilized space-time formulation is a very robust numerical technique for solving moving boundary problems. Tezduyar et al. (1992a, 1992b, 1992c) developed a staggered approach for solving the FIV problems in conjunction with stabilized space-time finite-element formulation. This formulation has been used successfully to predict the flow and body motion (Mittal and Tezduyar, 1992; Singh and Mittal, 2005; Prasanth and Mittal, 2008; Sen and Mittal, 2015, etc). The present work concerning undamped, transverse-only VIV of a thin elliptic cylinder also employs this formulation. The controlling non-dimensional parameters governing VIV of an elliptic cylinder are:

Geometric parameter

(i) aspect ratio, AR of ellipse: ratio of lengths of the minor and major axes of the ellipse. For the present study, $AR = 0.5$. The major axis, D of the ellipse (Fig. 1a) is used as the characteristic length scale.

Structural parameters

(ii) mass ratio or relative density of the oscillator, m^*: ratio of oscillator mass per unit length, m to mass of displaced fluid, m_d. For an elliptic cylinder of $AR = 0.5$, $m_d = \frac{\rho\pi D\frac{D}{2}}{4}$ where ρ is the density of fluid.

* Corresponding author.
E-mail address: ssen@iitism.ac.in (S. Sen).

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This leads to $m^* = \frac{8m}{\pi D^2 \rho}$ and $m^* = 10$ for the present computations.

(iii) reduced speed, U^*: the free-stream speed, U normalized with the natural/structural frequency, f_N of the oscillator and characteristic dimension, i.e. $U^* = \frac{U}{f_N D}$.

(iv) damping ratio or coefficient of structural damping, ζ: expressed as $\frac{c}{2\sqrt{km}}$. Here, c and k denote the damping and stiffness of the oscillator system. For undamped VIV, $\zeta = 0$.

flow parameter

(v) Reynolds number, Re: based on free-stream speed and characteristic dimension, i.e. $Re = \frac{UD}{\nu}$ where ν is the kinematic viscosity of the fluid.

In the present analysis, quantities (i), (ii), (iv) and (v) remain constant while the parameter (iii) is allowed to vary. The FIV of an elliptic section cylinder is yet to receive considerable attention. Only a handful of experimental and numerical investigations are available in the literature on this subject. These studies for instance, deal with incoming oscillatory flow past a stationary elliptic cylinder, forced in-line/transverse vibrations and single-degree-of-freedom (SDOF) or two-degrees-of-freedom (2-DOF) VIV. Accounts of earlier studies relating to all three types are provided below. Thereafter, a brief discussion highlighting the primary objectives of the current study marks the closure of Introduction.

1.1. Oscillatory incoming flow past a fixed elliptic cylinder

For symmetrically oriented (angle of incidence = 0° and 90°) fixed elliptic cylinders of $AR = 0.5 - 0.8$, Badr and Kocabiyik (1997) numerically investigated in two-dimensions, the streamwise oscillatory flow with reduced frequencies of π/4 and π/2 over a Reynolds number range of 200 − 1000. This study employed the streamfunction-vorticity formulation of the Navier-Stokes equations of motion. Detailed results were presented on time evolution of the symmetric flow field (about the streamwise axis of symmetry), surface pressure distribution and also the force coefficients.

1.2. Forced vibrations of elliptic cylinders

The earlier efforts to analyze forced vibrations of a symmetric elliptic cylinder were analytical investigations by Ray (1936) and Kanwal (1955). Ray (1936) considered in-line motion and Kanwal (1955) considered both the cases of in-line and transverse translations. Davidson and Riley (1972) semi-analytically studied the steady streaming motion of an initially stationary fluid induced by controlled transverse oscillations of symmetric elliptic cylinders about the major or minor axis. A jet-like flow that forms due to collision of outer boundary layers was found to appear along the axis of oscillation. They assumed that the collision occurs as long as the boundary layers are thinner than the elliptic cylinders. Using elliptic cylinders of $AR = 0.57, 0.75, 1, 1.33$ and 1.75, water tank experiments were also conducted at $Re \approx 300$ to determine the strength of the jet-like flow. Okajima et al. (1975) investigated the forced transverse vibrations of inclined elliptic cylinders of various AR. They performed finite-difference computations (for $Re = 40$ and 80) followed by experiments (for $Re = 40 - 20000$). They noted that the effect of Re on fluctuating fluid forces is insignificant at low incidence and it becomes prominent at large angles involving stall. Taneda (1977) provided flow visualization results for a 30° inclined elliptic cylinder of $AR = 0.5$ executing forced in-line oscillations at $Re = 48$ and 144. Through semi-analytical treatment of streamfunction-vorticity equations, D'Alessio et al. (1999) investigated the flow around an impulsively started thin elliptic cylinder of $AR = 0.1$ executing simultaneous in-line translations at constant velocity and controlled pitch oscillations with frequency 0.5. The study explores at $Re = 500$ and 1000, vortex-formation and shedding from the leading and trailing edges. The forced transverse vibrations of an inclined elliptic cylinder reported by Okajima et al. (1975) were later revisited through numerical experiments by D'Alessio and Kocabiyik (2001) for an $AR = 0.5$ cylinder at 45° and 90° incidences. For constant streamwise translation of the cylinder coupled with forced transverse oscillations, D'Alessio and Kocabiyik (2001) examined the effects of oscillatory to translational velocity ratio and angle of incidence on the evolution of wake. The Re was fixed to 1000. This study captures a phenomenon where multiple co-rotating vortex pairs appear. Such pairs form out of break up and merger of shed vortices in the near wake. This phenomenon is characteristic to 45° incidence alone. For an inclined elliptic cylinder of $AR = 0.5$ executing forced streamwise oscillations, Kocabiyik and D'Alessio (2004) investigated the flow characteristics at $Re = 1000$ using a semi-analytical technique. The vorticity equation was handled via finite-difference and streamfunction by a finite Fourier series. The angles of incidence considered were 30°, 45°, 60° and 90°. Two remarkably distinct families of vortex streets were identified in the near wake depending on whether the angle of incidence is smaller than 90° or equal to 90°. A regular Karman vortex street characterized by alternately shed counterrotating vortices appeared when the angle of incidence was below 90°. In contrast for 90° incidence, two pairs of vortices with each pair forming of like-signed vortices were shed in each oscillation cycle.

1.3. Free vibrations of elliptic cylinders

Franzini et al. (2009) conducted experiments to study the transverse-only vibrations of vertical elliptic and inclined circular cylinders of low mass ratio ($m^* \approx 2.5$). The range of Reynolds number was 2000–8000. For the elliptic cylinder, they identified three distinct response branches as function of the reduced speed. For $Re = 60–140$, Navrose et al. (2014) numerically explored the undamped VIV of symmetric elliptic cylinders of $m^* = 10$ and $0.7 \le AR \le 1.43$. They resolved seven distinct regimes of response. The sequence in which these regimes appear with increasing Re is - steady state (*SS*), desynchronization I (*DSI*), quasi-periodic initial branch, periodic initial branch, periodic lower branch, quasi-periodic lower branch and desynchronization II (*DSII*). The minimum range of lock-in and least value of maximum transverse displacement, Y_{max} of the ellipse were associated with $AR = 0.7$. For rigid elliptic cylinders of $AR = 0.5, 1, 2$ and $m^* = 10$, Hasheminejad and Jarrahi (2015) reported VIV results for $60 \le Re \le 400$. The computed the VIV for two-degrees-of-freedom motion of $m^* = 10$ cylinders. By performing space-time finite-element simulations, Sourav and Sen (2017) investigated the undamped (for transverse-only and 2-DOF) and damped (for transverse-only) free vibrations of a thick elliptic cylinder of $m^* = 1$. For each case, cylinder aspect ratio was 1.1. For oscillators involving with curved contours, Sourav and Sen (2017) possibly for the first time reported response curves free of secondary hysteresis.

1.4. Objectives of the current work and structure of the article

A bulk of literature is available on the response characteristics of common bluff obstacles, such as, circular and square section cylinders. However, little is known on VIV of oscillators behaving as streamlined objects. This lack of knowledge forms the basis of the current investigation. The motivation for the current work is derived from the following queries: does a flexibly mounted streamlined body execute VIV at an Re at which the flow around that body when held stationary is steady? How do Y_{max} and range of lock-in evolve for a streamlined oscillator when the AR is reduced below 0.7? Also arise the associated queries, such as, how do the response branches transform as AR continues to decrease? Is it possible that the cylinder ceases to translate below a certain AR? If a steady regime is present, how does the mean surface pressure, C_p vary in the steady and unsteady/VIV regimes? How does vortex-shedding affect the pressure at stagnation points, shoulders and in turn, the drag and lift forces? Why does the drag of a vibrating cylinder overshadow the ones from its stationary counterpart? To