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Wake instability modes for forced transverse oscillation of a sphere

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ABSTRACT

The present numerical study aims to identify the instability modes in the wake behind a transversely oscillating sphere with amplitude $A=0.5$ at Reynolds number $Re=300$. The governing equations are solved in the non-inertial frame using the immersed boundary method. The longitudinal thread-like structure is accompanied by asymmetric shedding before the onset of a “lock-in” regime. The wake is found to exhibit symmetric vortex shedding and organized chain like structures in the synchronized regime. Lesser flow inertia at a relatively low *Re* is dominated by the externally applied motion of the sphere resulting in negative energy transfer by the fluid to the sphere. In the synchronous regime different timing of vortex shedding and phases of coefficient of vortex with sphere motion demarcate two wake modes which have close resemblance with the modes found in induced vibration of a sphere.

1. Introduction

Flow-induced vibration is a physical phenomenon where flow of fluid around a structure generates significant and undesired motion to the structure. Blevins (1990) classified the flow-induced vibration by the nature of the flow and the structure. Vortex-induced vibration (VIV) is a class of flow-induced vibration, where the vortices interact with the structure and cause its oscillation. It is encountered as a design failure problem in bluff structures such as bridges, buildings, automobiles, electric power poles, telephone cables, heat-exchanger tubes, etc. Circular cylinder and sphere are the two simplest representatives of the real life bluff structures, but manifest almost all the physical phenomena. Intensive reviews have been made by Sarpkaya (1979, 2004), Bearman (1984), and Williamson and Govardhan (2004) on the VIV of a circular cylinder.

Williamson and Govardhan (1997) were the first to observe the dynamics of tethered spheres in a steady fluid flow. Vibration in the transverse direction was more vigorous (saturation amplitude of close to two diameters peak-to-peak) compared with that in the stream-wise direction. The frequency of oscillation in the stream-wise direction was twice the transverse oscillation frequency. The reduced velocity ($U^*=U/f_nD$) instead of the Reynolds number (*Re*), where U, f_n and D are the free-stream velocity, natural frequency of the system and the diameter of the sphere, respectively, was found as a more suitable parameter to scale the response amplitudes.

Embarking upon these observations Govardhan and Williamson (1997) characterized the transverse oscillations by the root-mean-square (rms) of the sphere's displacement instead of the amplitude. The rms response curve displayed a local peak followed by a saturation value. The local peak was explained as a resonance between the vortex shedding frequency from a stationary sphere (f_o) and f_n. Jauvtis et al. (2001) named these resonance condition and the saturation state as Modes I and II, respectively. They extended the works to higher mass ratio (m^*=sphere mass/displaced mass of fluid) and U^* feasible in wind tunnel instead of water channel. A new periodic response for ($20 \leq U^* \leq 40$) at $m^*=80$ was named as Mode III. They also discovered Mode IV response characterized by intermittent bursts of large-amplitude vibration beyond $U^*=100$.

All the researches so far were focused on the dynamics of sphere without associating the vortex dynamics in the wake. Govardhan and Williamson (2005) hereafter referred to as G–W were the first to report a chain of stream-wise vortex loops on alternating sides of the wake for the first three periodic responses. Modes I and II represented the synchronized regime, where the sphere's oscillation and the wake vortex shedding frequencies were synchronized (or tuned) to each other. Oscillations of the sphere in the vertical direction (z) were found to be less than 5% of that in the transverse direction (y). Response for a tethered sphere (xy motion) and hydroelastic sphere (y-only) compared well for similar mass-damping parameter $(m^*+C_A)\zeta$,

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where C_A is the potential added mass coefficient and ζ is the damping ratio.

Hout et al. (2010) discovered three bifurcation regions for a tethered sphere. In the first region, vortex shedding pattern was identical to that of a stationary sphere with no transverse oscillation. The second region was characterized by periodic and large amplitude transverse oscillation of half the sphere diameter. The vortex shedding and the wake structure were similar to that observed by G–W in the second region. For the third region, the sphere exhibited non-stationary oscillations in the transverse direction. Second bifurcation region overlapped with Modes I and II, while the third bifurcation region was linked to Mode IV.

Numerical investigation of Behara et al. (2011) at $Re=300$ observed shedding of spiral vortices in addition to the hairpin vortices reported in G–W. Eshbal et al. (2012) observed an increase of fragmented vortical structures as Re increased from 550 to 1925. This increase of fragmented vortical structures was attributed to the increase in shear layer instabilities. Numerical and experimental study by Lee et al. (2013) showed the existence of seven different flow regimes for $50 \le Re \lesssim 1200$. These regimes do not have any relation with the four modes previously reported. Entirely different observations are attributed to the use of neutrally buoyant tethered sphere instead of the light and heavy spheres. An interesting observation was made by Williamson and Govardhan (1997) and G–W that the flow remains same in the range $2000 \le Re \le 12\,000$.

The aim of this work is to identify and study the wake instability modes for forced transverse oscillation of a sphere at $Re=300$. In the following sections we shall establish a correlation between the modes revealed and those found in VIV of a sphere. The energy transferred from the fluid to the sphere is found to be negative which is explained by revealing two mechanisms of forcing in Section 3.2. In the next section the governing equations are followed by a brief discussion on the numerical technique employed. In Section 3 three wake instability modes are analyzed based on time traces of force coefficients, phases and energy transfer rates. Vortex shedding modes, instantaneous wake structures, are shown and discussed in Section 4 in order to characterize the near wake region. Finally the principal findings of the present work are summarized in Section 5.

2. Problem set-up

A sphere of diameter D placed in a stream-wise (x) uniform flow (U) transversely (y) oscillates with a forcing frequency $f_e = f_R f_o$, where f_R, f_o are frequency ratio and the natural shedding

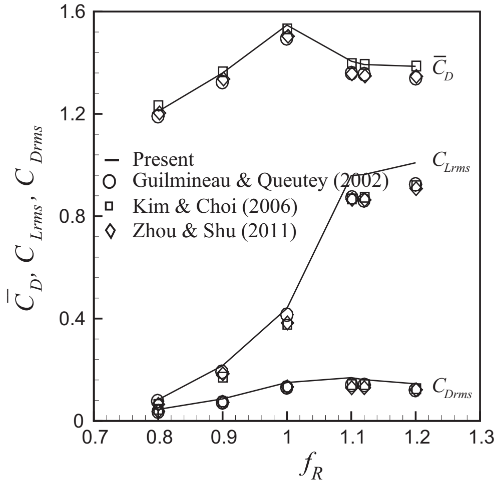

Fig. 2. Comparison of computed global flow parameters for forced transverse oscillation of a circular cylinder with reported results.

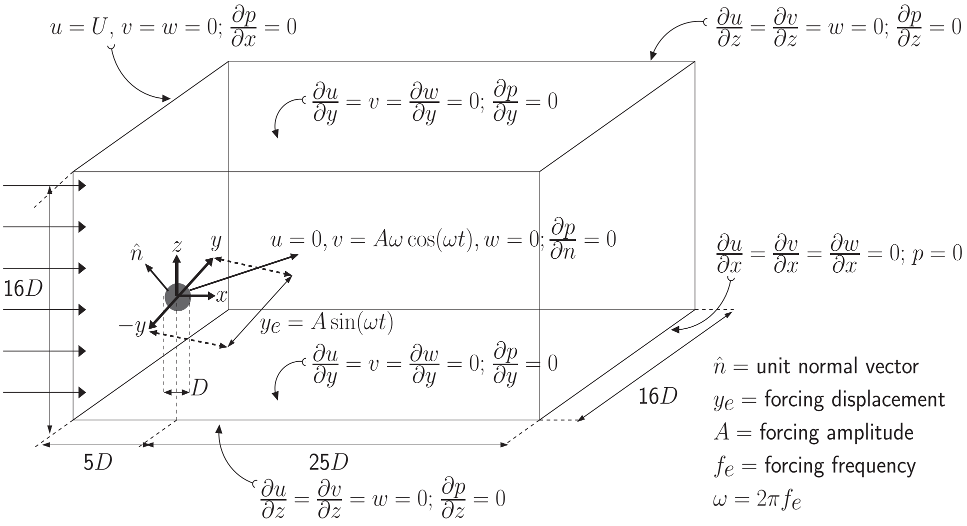

Fig. 1. Schematic diagram for the forced transverse oscillation of a sphere.

Table 1
Comparison of computed global flow parameters for flow past a stationary sphere at $Re=300$ with reported results.

Work	$\langle C_D \rangle$	$\langle C_L \rangle$	St
Present	0.659	−0.069	0.137
Johnson and Patel (1999)	0.656	−0.069	0.137
Kim et al. (2001)	0.657	0.067	0.134