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Free vibrations of a square cylinder of varying mass ratios

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Abstract

Two-dimensional space-time finite-element simulations are carried out to study the effect of oscillator mass ratio, m^* on free in-line and transverse vibrations of a rigid square cylinder. The effect of viscous damping or resistance is not considered and thus cylinders of mass ratio 1, 5, 10 and 20 execute free undamped vibrations. Results are presented for $50 \leq Re \leq 250$ where *Re* is the Reynolds number. For $m^* = 1$, synchronization between cylinder oscillation and vortex-shedding is 1:1 (periodic flow). Thus, the C_l-Y phase portraits must be single looped closed curves. For $m^* = 5$-20, synchronization is 1:1 (periodic flow) prior to galloping. For $m^* = 5$, the synchronization during galloping is quite different from 1:3. Along 'increasing *Re*', the entire galloping branch of $m^* = 5$ cylinder is quasi-periodic. However, along 'decreasing *Re*', it is mostly quasi-periodic and it is periodic for $Re \leq 190$. An 1:3 sub-harmonic synchronization is seen for the $m^* = 10$ and 20 cylinders only in the periodic regime of galloping occurring at higher *Re*. For $m^* = 1$, only one kink is seen in the response curve signifying transition from initial to lower branch. Two kinks are captured for $m^* = 5$ cylinder. For $m^* = 10$ and 20, an additional third kink is resolved in the galloping branch that signifies transition from quasi-periodic flow/body motion to periodic flow/body motion.

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1. Introduction

The vortex-induced vibration (VIV) of a flexibly mounted rigid body is a major research area belonging to fluid-structure interactions. Galloping instability characterized by large amplitude and low frequency self-excited oscillations differs from VIV. Besides the oscillator cross-section, the non-dimensional parameters of interest in fluid-structure interactions include mass ratio, m^*; coefficient of structural damping, ζ; reduced speed, U^* and Reynolds number, *Re*. Mass ratio is the ratio of oscillator mass per unit length and mass of displaced fluid.

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[1] conducted aeroelastic experiments on free transverse-only oscillations of a rigid square cylinder of large mass ratio and low structural damping. Two-degrees-of-freedom free hydroelastic vibrations of a rigid square cylinder of $m^* = 10$ was numerically studied by [4]. While free vibrations of a circular cylinder have been investigated for varying mass ratios ([3], [10], etc), similar studies for a square cylinder are hardly available in the literature. [2] presented very limited results for a freely vibrating square cylinder with $m^* = 5$, 10 and 20. They numerically explored the effects of mass ratio on lock-in, response and forces on a square cylinder. For a freely vibrating square cylinder of mass ratio = 2.64 and inclined to the free-stream at 0^0, 20^0 and 45^0, [9] presented experimental results at high Reynolds numbers ranging between 2000 and 13000. This study provides a detailed account of wake modes and various synchronization patterns available for each angle of incidence. Table 1 lists some of the earlier studies concerning effects of m^* on VIV.

As an extension of their earlier work [4] on free vibrations of a square cylinder at zero incidence, [5] recently studied the effects of mass ratio on free vibration characteristics. For a zero viscous damping situation ($\zeta = 0$) and two-degrees-of-freedom motion of cylinder, the study employed the key parameters as: Re = 50-250 and m^* = 1, 5, 10 and 20. This study predicts perhaps for the first time, the value of threshold transverse response (~$0.7D$ where D is the edge length of square) marking the appearance of 2P+2S wake vortex mode for a galloping square cylinder. The mass ratio as a major influencing parameter governing the regime of vibrations (VIV or VIV followed by galloping) is explored by [5]. The current study is closely linked to the recent work of [5]. With the aid of some new results this work attempts to provide further details of the low Re vortex-induced motion of sharp edged square cylinders. The motivation for this extension is derived from certain queries: what types of synchronization can be identified as a function of mass ratio? How many transitions occur as Re is increased? Do the transitions depend on mass ratio? What are the possible wake modes for a freely vibrating square cylinder at low Re? Why cannot we expect the 2P or P+S modes to form in the square cylinder wake? Efforts are made here to answer the above questions.

Table 1: Some earlier studies on effects of m^* on VIV of rigid circular and square cylinders. Here, X and Y represent in-line and transverse displacements, respectively (see Fig. 1). The first study is based on experiments while the rest followed computational techniques.

Cross-section	Study	Re	m^*	ζ	Motion
Circular	[3]	1000-15000	1.5-25	0.0000385-0.04	X-Y
Circular	[10]	50-400	1, 2, 5, 10, 50	0	Y-only
Square	[2]	60-250	5, 10, 20	0	X-Y
Square	[5]	50-250	1, 5, 10, 20	0	X-Y

2. Methodology

The two-dimensional incompressible Navier-Stokes equations of motion are solved to find the flow field. The dynamics of the cylinder is determined from the ODEs for rigid body motion along the in-line and cross-stream directions. A stabilized space-time finite-element formulation accommodating equal order interpolation for velocity and pressure is used. The interpolation functions are bilinear in space and linear in time. Globally, these interpolation functions are continuous in space but discontinuous in time. Details of the space-time finite-element formulation can be found in [6, 7]. The square cylinder resides in a rectangular computational domain (see Fig. 1). A fixed or inertial frame of reference (here, Cartesian) is used for the analysis of flow and cylinder motion. In the figure, u and v are the Cartesian components of fluid velocity, σ is the stress tensor, H is the width of the channel