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Experimental study on transverse flow-induced oscillations of a square-section cylinder at low mass ratio and low damping

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ABSTRACT

This article presents experimental results concerning the transverse flow-induced oscillations of a square-section cylinder for several values of the mass ratio, ranging from 2.2 to 14.4, and low mechanical damping. Experiments were carried out in a re-circulated free-surface water channel. A rigid square-section cylinder was fixed to an elastic system made with dual (parallel) metallic blades connected by a rigid block. By this way the square-section cylinder is free to oscillate in the transverse (normal to flow) direction. The elastic system presents linear behavior in terms of stiffness and damping. The functional dependence between the steady-state amplitude and frequency of oscillations with reduced velocity is characterized. A re-normalization plot appears when steady-state amplitude of oscillations is plotted against the "true" reduced velocity, which is defined as the reduced velocity divided by the dimensionless frequency of oscillations. Experiments also allow to discuss other aspects, like the reduced velocity at which oscillations are expected to start depending on the value of the mass ratio, how close to sinusoidal (say, fixed amplitude and frequency) the oscillations are, or when quasi-steady conditions are expected to be met.

1. Introduction

Flow induced vibration (FIV) of bluff bodies is a topic of interest from both scientific and engineering sides. In engineering applications, most structures have a bluff cross-section and, most of the time, they are under the action of wind or water flows which makes mandatory to estimate properly the fluid loading on the structure and its response. When considering scientific aspects, the problem is very rich: the bluff body under fluid flow sheds, for high enough Reynolds numbers, large-scale vortices which create an unsteady fluid loading on the body surface which can induce vibrations to the body. Then, there is a very complex interaction between the incoming flow and body response, which depends mainly on the shape of the body, structural (mechanical) properties of the body, and flow speed. The circular cylinder has been the bluff geometry which has been studied more intensively to date, because circular beams are common structural elements but also because of its inherent symmetry. A single isolated circular cylinder can be excited mainly by Vortex-Induced Vibrations (VIV) but also by buffeting if turbulence in the inflow is high enough. Two circular cylinders arranged in tandem can be excited by Wake-Induced Vibrations (WIV). Reviews on VIV of circular cylinders are given by Sarpkaya [1] and Williamson and Govardham [2]; for a detailed introduction to WIV the reader is referred to Sumner [3] or Assi et al. [4,5].

Non-axisymmetric cross-sections can be excited by VIV as well as other FIV phenomena, like galloping (Naudascher and Rockwell [6]). Galloping is a motion-induced instability that appears in some elastic bluff bodies (square cross-section at a zero-angle of attack for example) when the velocity of the flow exceeds a certain critical value. Then, a small transverse displacement of the body induces an angle of attack relative to the incoming flow and an asymmetric pressure distribution, so that fluid force appears in the direction of the displacement in such a way that energy is transferred from the current to the body and oscillatory motion (mainly transverse to the unperturbed flow) develops. Unlike VIV, which occurs only in a certain range of flow velocities and with self-limited amplitude, galloping takes place for any value of the flow velocity higher than the critical value and has a monotonic increase of amplitude with flow velocity.

The study of galloping has been traditionally focused on situations where the mass ratio m^*, the ratio of mean body density to fluid density, is large, which is the case when airstreams are considered ($m^* \gtrsim 50$, for instance, for a light material 50 times the density of the air). Under such circumstances, a successful

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theoretical approach to the problem is possible by resorting to the quasi-steady hypothesis (Parkinson and Smith [7], Barrero-Gil et al. [8,9]). Quasi-steady hypothesis assumes that fluid forces are determined by the instantaneous attitude of the body (angle of attack) with respect to the incoming flow, and it may be expressed as a polynomial of the velocity of body oscillations [10]. This means that fluid force is in phase with the velocity of body oscillations at any instant and, therefore, the phase lag between fluid force and body displacement is 90° [11]. It is traditionally considered that quasi-steady conditions can be resorted to when the characteristic convective time of the flow is small compared with the characteristic time of oscillations. However, studies on galloping for situations at which $m^* \sim 1$ (say hydroelastic) are scarce even though they occur in many practical situations (think, for example, in the case of prismatic structural members in water currents [12]).

To our knowledge, it was Bouclin [13], in collaboration with Parkinson, who were first interested in galloping features of a square-section when $m^* \sim 1$. They performed hydro-elastic experiments with a spring-mounted square-section cylinder of side length D and submerged length L in a free-surface recirculating water channel for three different values of m^* (4.2, 8.5, and 14) and low structural damping. The square-section cylinder was restricted to move transverse to the incoming flow direction. Their results were given in terms of normalized amplitude $A^* = \sqrt{2}A_{RMS}/D$ and frequency $f^* = f/f_N$ of steady oscillations (A_{RMS} is the root mean square value of amplitude of oscillations and f_N is the frequency of oscillations of the square-section cylinder in still water). They found a quasi-linear dependence of A^* with the reduced velocity $U^* = U/(f_N D)$ (U is the speed of the unperturbed flow), quite independent of the mechanical damping. They also found that a good collapse of data seems to occur when re-normalized quantities $A\prime = A^*/(2m^*)$ and $U\prime = U^*/(4\pi m^*)$ are introduced. More recently, Nemes et al. [14] and Zhao et at. [15] carried out additional experiments in a water channel for lower values of the mass ratio, $m^* = 2.2$ and $m^* = 2.6$, respectively. In these cases, normalized amplitude were reported as $A^* = A_{10}/D$, where A_{10} is the mean of the top 10% of the peaks (Hover et al. [16]). They found a quasi-linear dependence of A' with U' except in a region where a 1:3 synchronization with vortex shedding fluid loading seems to occur. However, for a fixed value of U', values of A' measured by Nemes et al. [14] and Zhao et at. [15] seem to be higher than those observed by Bouclin [13] (see Fig. 1). In other words, from Bouclin's data one finds that $A' \approx 0.36U'$, but from Nemes's and Zhao's experiments (with a lower value of m*) one finds that $A' \approx 0.46U'$. This point was noted in Nemes et al. [14] who suggested that the reason for the differences could be ascribed to the different experimental conditions, such as turbulence intensity, surface roughness, aspect ratio, end condition, and blockage ratio. We agree with this statement but also wanted to test whether, in this range of parameters, the constant of proportionality between A' and U' depends on m^*. In an attempt to get insight into this point we have carried out an experimental campaign in a re-circulating free-surface water channel of the transverse-induced oscillations of a square-section cylinder for several values of the mass ratio, ranging from 2.2 to 14.4, and low mechanical damping. We have found that A' depends on U' but also, to a lesser extent, on m^*. Since this two parameter dependency might be relevant for some practical design applications of marine and river structures, we have characterized its functional behavior. Experimental results also allow us to introduce a re-normalized plot where a reasonable collapse of all experimental data takes place, as well as to get insight on other questions, such as up to what extent the oscillations can be characterized in terms of time-averaged quantities (amplitude and frequency), at which reduced velocity oscillations are expected to start, or when the quasi-steady hypothesis can be resorted to.

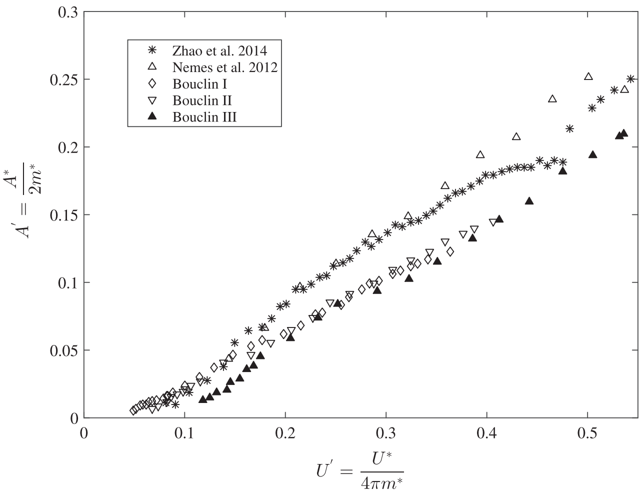

Fig. 1. Variation of A' with U'. Open diamonds represents $m^* = 4.2$, filled triangles represent $m^* = 8.5$ and inverted triangles represent $m^* = 14$ from Bouclin [13]. m^* was 2.2 in experiments from Nemes et al. [14] and $m^* = 2.6$ in Zhao et al. [15].

The rest of the article is organized as follows: the experimental method and apparatus, acquisition procedures, and validation tests are detailed in the following section. Experimental results for the square section are presented and discussed in Section 3; an empirical law is proposed to estimate amplitude and frequency of oscillations as a function of both the reduced velocity and mass ratio. In addition, the level of fluctuations in the oscillations and the validity of the quasi-steady hypothesis are discussed. Finally, concluding remarks are presented in Section 4.

2. Experimental set-up and validation

2.1. Experimental apparatus

The experiments were carried out in a free-surface recirculating water channel with controlled inflow conditions at the test section in terms of mean speed, uniformity, and low turbulence. A sketch of the water channel is shown in Fig. 2. The water is driven by two equal axial pumps from ABS, model RCP 500 ($Q_{max} = 0.69\ \mathrm{m^3/s}$, $\Delta p_{max} = 13000$ Pa, $P_{max} = 11$ kW). The rotation speed of the axial pumps is regulated by a variable frequency drive from Power Electronics (model SD503942) in such a way that the water channel velocity at the test section can be controlled in a range from 3 cm/s to 110 cm/s. The test section is made of glass and allows for the flow to be viewed from either side, as well as the bottom. Guide vanes are placed in the corners in order to guide the flow and reduce pressure-losses. To improve the flow quality in the test section both a honeycomb (hexagonally shaped cells with a diameter of 4.5 mm and a length to diameter ratio of 12) and a screen are located before the entrance of the test section. The honeycomb is a very effective flow straightening device with a length above 10 cell diameters as shown by Bradshaw and Pankhurst [17] and the screen is effective to reduce mean non-uniformities and fluctuations of the streamwise component.

A square-section cylinder (B) of side length D = 20 mm, made of aluminum, was fixed vertically to the free end of a double-blade elastic system, which follows the arrangement introduced in Assi et al. [18]; see Fig. 3. The square-section cylinder had an immersed length L of 820 mm, and was furnished with a circular endplate (C) with diameter of 75 mm to enhance two-dimensional flow. The elastic system was made up of with two parallel rigid aluminum blocks (D), coupled to a pair of thin spring-steel flexor blades (E).