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Brief Communication

Transverse galloping at low Reynolds numbers

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Abstract

The possibility of transverse galloping of a square cylinder at low Reynolds numbers (Re $\leq$ 200, so that the flow is presumably laminar) is analysed. Transverse galloping is here considered as a one-degree-of-freedom oscillator subjected to fluid forces, which are described by using the quasi-steady hypothesis (time-averaged data are extracted from previous numerical simulations). Approximate solutions are obtained by means of the method of Krylov-Bogoliubov, with two major conclusions: (i) a square cylinder cannot gallop below a Reynolds number of 159 and (ii) in the range 159 $\leq$ Re $\leq$ 200 the response exhibits no hysteresis.

Keywords: Transverse galloping; Laminar flow; Square cylinder

1. Introduction

Among the broad variety of phenomena that flow can induce on structures, transverse galloping is well known to engineers (Simiu and Scanlan, 1978). This is an hydro/aeroelastic instability produced by the interaction of the lateral motion of the elastic body (structure) and the incident flow. Generally, transverse galloping can occur with long elastic bodies of aerodynamically bluff cross-section (non-circular) when the velocity of the incident flow exceeds a certain critical value. Then, the stabilizing effect of structural damping is overcome by the destabilizing effect of the fluid force and an oscillatory motion (normal to the wind flow) develops. This oscillatory motion increases in amplitude until the energy dissipated per cycle by structural damping balances the energy input per cycle from the flow. Sometimes, this amplitude can be many times the characteristic transverse dimension of the structure. Moreover, under certain conditions there is some oscillation hysteresis in the galloping behaviour for a range of flow velocities. This characteristic was observed for the first time by Parkinson (1961, 1964) in the course of laboratory experiments. When hysteresis takes place, multiple solutions for the amplitude of oscillation can appear for a range of flow velocities, depending on whether the flow velocity is increasing or decreasing. Most of the early interest in transverse galloping was directly related to the electrical lines and galloping oscillations sometimes observed when the ice accretion on the wires modified their initially almost circular sections. Thereafter, attention broadened to situations where the phenomenon has also been observed: marine pipelines (Simpson, 1972), traffic signs and signal supports (Johns and Dexter, 1998), gates with underflow (Nguyen and Naudascher, 1986), and some metallic structures (Mahrenholtz and Bardowicks, 1980).

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There is a large body of theoretical and experimental work concerning transverse galloping, much of which is reviewed in Parkinson (1974), Blevins (1990) and Naudascher and Rockwell (1994). For example, large efforts have been devoted to study the galloping features: the influence of the geometry of the cross-section (Novak, 1969, 1972), the influence of the incident turbulence (Novak and Tanaka, 1974), the limits of the quasi-steady hypothesis (Nakamura and Matsukawa, 1987; Hémon and Santi, 2000), or the hysteresis phenomenon (Luo et al., 2003; Barrero-Gil et al., 2009). Those studies are focused in the high Reynolds number (Re) regime and, generally, discarding its effect (many bluff cross-sections have fixed separations points and traditionally the mean flow has been considered, at a first approximation, as Reynolds number independent). However recently, Macdonald and Larose (2006, 2008) have taken into account the Re effect for the case of cable galloping. Near the critical Reynolds number (when the boundary layer upstream of separation changes from laminar to turbulent) a circular cylinder can generate lift. To account for this phenomenon, Macdonald and Larose in their analysis introduced a Re dependence and they showed how a circular cylinder (dry cable) can gallop in a narrow range of Reynolds number (around $270\,000<\mathrm{Re}<360\,000$). Nevertheless, the low Reynolds number regime has not received much attention. We believe that this regime may appear in practical situations, for low flow velocities or when the characteristic length scale of the body is small: for example, for an elastic body with a characteristic length of the cross-section of $D = 1$ mm, and under the action of an airstream with velocity $U = 1$ m/s, the Reynolds number is $\mathrm{Re} = UD/\nu = 100$ (ν is the kinematic viscosity). Based on Sohankar's numerical simulations on the low Reynolds number flow around a square cylinder (Sohankar et al., 1998), the aim of this brief communication is to address two questions:

(i) Can transverse galloping appear at low Reynolds number (laminar regime) for a square section?
(ii) If so, what kind of response exists (whether hysteresis appears or not)?

Following a description of the mathematical modelling of transverse galloping in the next section (Section 2), we use numerical data to study the possibility of transverse galloping and, for those affirmative cases, the body response (Section 3). Finally, some conclusions are drawn.

2. Mathematical modelling of transverse galloping

The description of the behaviour of an elastic body under the action of an incident flow is an extremely complex problem; however, in some cases its modelling can be simplified in order to make an analytical study feasible. Common assumptions are (Parkinson, 1974): (i) the structure is described as a linear oscillator of one-degree-of-freedom (the possibility of rotational motion is not considered), (ii) the structure is sufficiently slender to consider two-dimensional flow, and (iii) that the incident flow is free of turbulence. Under these conditions, the equation governing the dynamics of the transverse galloping represents a balance between inertial, damping, stiffness, and fluid forces (Blevins, 1990):

$$m(\ddot{y} + 2\zeta\omega_y\dot{y} + \omega_y^2 y) = F_y = \tfrac{1}{2}\rho U^2 D C_y, \tag{1}$$

where y denotes the transverse displacement (vertical), m is the body mass per unit length, ζ is the dimensionless structural damping coefficient, ω_y is the undamped natural frequency, ρ is the fluid density, which will be considered constant throughout the analysis, U is the velocity of the incident flow, D is the characteristic dimension of the structure in the direction of the flow (here, D is the side-length of the square cylinder), and C_y is the instantaneous fluid force coefficient in the normal direction to the incident flow; finally, the overdot stands for differentiation with respect to time t.

The fluid force is evaluated by resorting to the quasi-steady assumption, whose use is justified when the following conditions are satisfied:

(i) The characteristic timescale of the body oscillations T_y ($\sim 1/f_y$, where f_y is the natural frequency of oscillations) is much larger than the characteristic timescale of the flow T_R (residence time), of order D/U. Taking as above (Section 1) $U = 1$m/s, $D = 1$ mm, and $f_y = 1$ Hz, then a reduced velocity $U_R = U/(f_y D) = T_y/T_R = 1000$ is obtained (high enough to consider quasi-steady conditions).
(ii) The vortex shedding frequency f_t is much higher than the frequency of oscillations. $f_t \sim U\mathrm{St}/D$, where St is the Strouhal number. For a square section, and the Reynolds numbers considered, a representative value of $\mathrm{St} = 0.1$ can be assumed (Okajima, 1982). Then $f_t \sim 100\,\mathrm{Hz} \gg f_y$.

Thus, the fluid force is completely determined by the instantaneous velocity of oscillation of the structure, and fluid force data in the static case can be used and they can be related to the motion of the body.