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Interference of vortex-induced vibration and transverse galloping for a rectangular cylinder

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ABSTRACT

The phenomenon of interference between vortex-induced vibration (VIV) and galloping in the transverse degree of freedom was studied in the wind tunnel in the case of a spring-mounted slender rectangular cylinder with a side ratio of 1.5 having the short side perpendicular to the flow. The tests were carried out in a wide Scruton number range, starting from low values and increasing it in small steps by using eddy-current viscous dampers. This study helped understanding the dynamics of the interaction between the two excitation mechanisms and clearly highlighted the transition through four regimes of VIV-galloping interference. It was found that a high value of the mass-damping parameter is required to decouple the ranges of excitation of vortex-induced vibration and galloping completely, and for the quasi-steady theory to predict the galloping critical wind speed correctly. This conclusion is also relevant from the engineering point of view, as it means that structures and structural elements with ordinary mass-damping properties can exhibit sustained vibrations in flow speed ranges where no excitation is predicted by classical theories of vortex-induced vibration and galloping. Although most of the experimental tests were conducted in smooth flow at zero angle of attack, the paper also discusses the sensitivity of the results to a small variation of the mean flow incidence and to the presence of a low-intensity free-stream turbulence.

1. Introduction

Slender prismatic and nearly-prismatic bodies characterized by a bluff cross section with sufficient afterbody are prone to both vortex-induced vibration (VIV) and galloping. Galloping instability in the transverse degree of freedom usually occurs at high reduced flow speed and is therefore approached with the quasi-steady theory. By contrast, vortex-induced vibration is a low-reduced-flow-speed phenomenon. Nevertheless, if the oscillating structure is light and low damped, *i.e.* the dissipation capability of the system is low, three important consequences can ensue: (i) vortex-induced vibrations may occur with large amplitudes in a wide range of flow speeds; (ii) the onset of VIV and galloping may be expected at close flow speeds and the two phenomena may interfere with each other; (iii) the quasi-steady theory could fail to predict the galloping instability threshold and the post-critical oscillatory behavior, due to the insufficiently high reduced flow speed.

In the case of rectangular cylinders in smooth flow with side ratios $0.75 \lesssim B/D \lesssim 3$ (Parkinson, 1965), B and D being respectively the streamwise and cross-flow section dimensions, a peculiar instability spawned by the interference of VIV

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and galloping can easily occur in the transverse mode (Washizu et al., 1978 observed galloping up to $B/D = 2.5$, while Nakamura and Tomonari, 1977 confirmed $B/D = 0.75$ as the lower side ratio for the galloping oscillations to arise spontaneously from rest). This phenomenon was consciously discussed for the first time by Parkinson and Sullivan (1979) for three-dimensional towers and Parkinson and Wawzonek (1981) for two-dimensional cylinders. It features sustained vibrations starting at the Kármán-vortex resonance flow speed, in the same way as VIV, but without self-limited amplitudes, as typical for galloping. An instability with these characteristics can occur even when the theoretical galloping critical flow speed (calculated with the quasi-steady theory) is significantly larger than the vortex-resonance flow speed, *i.e.* for relatively high values of nondimensional mass and mechanical damping of the system. This behavior implies large-amplitude oscillations for flow speeds at which no excitation is predicted by the classical theories, with important consequences also from the practical engineering point of view (Mannini et al., 2016).

For an extensive literature review about the interference of VIV and galloping, one can refer to Mannini et al. (2014), where many records of experiments with clear evidence of the phenomenon can be found. Therein, the complicated role of turbulence, the debated issue of frequency capture and the particular case of tree-dimensional towers are also discussed. However, the limits of applicability of the quasi-steady theory is a crucial turning point for the VIV-galloping interference phenomenon and a few additional literature works have to be mentioned here. In particular, Nakamura and Mizota (1975) performed forced-vibration tests showing that reduced flow speeds (defined as $U = V/n_0 D$, V being the free-stream flow speed, n_0 the vibration frequency in Hz and D the cross-flow model section dimension) greater than 20 for a square cylinder and 30 for rectangular cylinders with side ratios of 2 and 4 are required for the quasi-steady theory to give a good prediction of the lift force component in quadrature with the motion. Nevertheless, they noted that reduced flow speeds higher than about 60 are necessary for the phase angle between the transverse force and the model displacement to attain the quasi-steady theoretical value of 90°. A similar result was also obtained by Otsuki et al. (1974), Washizu et al. (1978) and Carassale et al. (2015). Nevertheless, the latter showed that the experimental results are in disagreement with the quasi-steady theory, even at high reduced velocity, if an angle of attack of 6° or more is imposed to a square cylinder. Bearman et al. (1987) claimed that the flow-induced oscillation phenomena of a square cylinder can be reasonably predicted through the quasi-steady approach for reduced flow speed beyond the galloping critical threshold, if the latter is about four times greater than the vortex-resonance flow speed. Luo and Bearman (1990) explained that the discrepancy between the experimental measurements and the theoretical prediction is mainly due to the effect of fluid inertia and the presence of shed vorticity, which are not accounted for. Hémon (1997) and Hémon and Santi (2002) proposed a modification of the quasi-steady approach, introducing a time lag between the transverse force and the oscillation velocity that is supposed to depend on the Strouhal frequency.

In this paper the interference of vortex-induced vibration and galloping is studied through experiments in the wind tunnel on a rectangular cylinder with a side ratio of 1.5, the shorter side facing the flow. Compared to the more widely studied square cylinder, this geometry exhibits galloping oscillations of slightly smaller amplitude, especially in turbulent flow (Parkinson, 1989). Nevertheless, it was chosen for the strong proneness to galloping instability (high slope in the origin of the static transverse force coefficient, see Section 3.1) and the tendency of VIV and galloping excitation mechanisms to interact also for rather high Scruton numbers (Parkinson and Wawzonek, 1981; Mannini et al., 2016).

A motivation for the present study stems from the work carried out by some previous research groups (*e.g.*, Parkinson and Wawzonek, 1981; Bearman et al., 1987), which suggests the need to investigate in detail the behavior of a flexibly mounted rectangular cylinder while the system mechanical damping is varied in small steps (in the present work, using eddy-current viscous dampers), so to shed some light on the complicated features of the VIV-galloping interference phenomena. To accomplish this task, an experimental set-up was designed to test configurations as adherent as possible to the ideal system investigated (linear mechanical system allowing for one-degree-of-freedom large-amplitude oscillations, very low damping in the starting configuration, reliable added damping device, smooth two-dimensional flow conditions, and negligible blockage effects). This was particularly important in view of the strong sensitivity of the body response to mechanical or aerodynamic disturbances in the transitional Scruton number range, wherein the VIV and galloping excitation mechanisms start to decouple. Unfortunately, this required to renounce to the measurement of the fluctuating pressures acting on the oscillating body.

In this work the tests were mainly performed in smooth flow at zero angle of attack but, as a sensitivity study, some configurations were also studied by imposing a small flow incidence and in a low turbulence incoming wind. The results are believed to be of interest from both the pure scientific and the practicing engineering point of view. In addition, most of the conclusions that can be drawn from this experimental campaign are expected to have a general validity, from a qualitative standpoint, for rectangular cylinders of similar side ratio. The study may also be relevant for energy-harvesting applications, which have been attracting growing attention in the scientific community.

2. Wind tunnel tests

2.1. Wind tunnel facility and model

The tests were carried out in the open-circuit boundary-layer wind tunnel of CRIACIV in Prato, Italy. The facility presents at the inlet a convergent with a contraction ratio of 3 to 1 after the honeycomb and a T-diffuser at the outlet. The rectangular