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# Unsteady galloping of a rectangular cylinder in turbulent flow

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ABSTRACT

Slender structures with a bluff non-axisymmetric cross-section are prone to both vortex-induced vibration (VIV) and transverse galloping. When the mass-damping parameter of the system is low, the two phenomena can interfere giving rise to a peculiar type of instability, for which the quasi-steady theory does not apply, and therefore which one may call “unsteady galloping”. Since for large structures (such as high-rise towers or bridge pylons) this phenomenon seems to be potentially an issue, rather than the quasi-steady galloping, it is particularly important to verify whether the former also occurs in realistic turbulent wind flows, and to understand its specific features. With this aim in mind, static and dynamic wind tunnel tests have been carried out on a two-dimensional rectangular cylinder with a side ratio of 1.5 (having the short side perpendicular to the flow) immersed in various grid-induced homogeneous isotropic turbulent flows. From a quasi-steady perspective, the static tests showed the proneness to galloping instability of the considered cross-section even in highly turbulent flow, though strongly dependent on the integral length scale of turbulence. In addition, they revealed an attenuation of the strength of vortex shedding, but suggested an increased tendency of VIV and galloping to interfere as compared to the smooth-flow case. The dynamic tests confirmed this tendency and highlighted a complicated behavior of the model in turbulent flow, with some features that still remain unexplained. In particular, even larger values of the mass-damping parameter of the system are necessary for the quasi-steady theory to be able to predict correctly the galloping instability threshold. Another important result is that the integral scale of turbulence was found to play a key role also in the unsteady galloping behavior of the considered rectangular cylinder.

## 1. Introduction

Vortex-induced vibration (VIV) and transverse galloping are well-known phenomena in the fields of bluff-body aerodynamics and wind engineering. VIV is a high-reduced-frequency phenomenon triggered by vortex resonance, which is addressed with unsteady approaches (see *e.g.* Marra et al. (2015)). In contrast, galloping in the transverse degree of freedom is usually considered a low-reduced-frequency instability, so that traditionally the well-known quasi-steady theory is applied (Parkinson and Brooks, 1961; Parkinson and Smith, 1964). However, it is expected that the quasi-steady approach becomes first inaccurate and then inapplicable when the mass-damping parameter of the system (often called Scruton number, and indicated with $Sc$) is progressively decreased. Indeed, the theoretical galloping critical flow speed linearly diminishes with $Sc$ and, beyond a certain value, the effect of vortex shedding can no longer be neglected (Parkinson and Wawzonek, 1981). When this interference occurs, one may address the ensuing instability as “unsteady galloping” (see *e.g.* Gao and Zhu (2017)).

Recently, the interference of vortex shedding and galloping was encountered in a practical structural engineering problem (Mannini et al., 2016a), and the phenomenon was carefully reviewed and discussed in Mannini et al. (2014) focusing on the particular case of rectangular cross sections. Moreover, the wind tunnel tests conducted in smooth flow on the sectional model of a rectangular cylinder with a side ratio of 1.5, having the short side perpendicular to the flow, showed the peculiarities of the unsteady galloping instability (Mannini et al., 2014, 2015), the most distinctive feature being the onset of the instability branch at the Kármán-vortex-resonance flow speed. Further experimental results highlighted in details the transitional behavior observed varying the Scruton number in small steps (Mannini et al., 2016b). In particular, it was found that values of the mass-damping parameter much larger than expected are required to decouple the mechanisms of excitation of vortex-induced vibration and galloping. In addition, the results clarified that such an interaction produces significant effects even in flow speed ranges quite apart from the vortex-resonance region. Finally, a modified version of the nonlinear wake-oscillator model of Tamura and Shimada (1987) was applied to the considered rectangular-section case study, obtaining promising results (Mannini et al., 2018). In particular, the

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mathematical modelling of the phenomenon helped in shedding some light on the basic mechanism through which vortex shedding and galloping interfere.

In spite of the progress made, from the wind engineering point of view two important questions still remain either partially or nearly completely unanswered, both concerning the effect of turbulence. The first one regards the quasi-steady galloping behavior of rectangular cylinders with side ratio close to unity: are these bluff bodies highly unstable in turbulent flow as well? If so, the second question arises about the actual significance and features of the interference with vortex shedding in realistic wind flows. An answer to these issues is sought in the present work, trying to distinguish between small- and large-scale turbulence. The former is known to play the major role in the modification of the aerodynamics of bluff bodies (see Mannini et al. (2017) for a short review on this subject, as well as the recent experimental results reported in Lander et al. (2016)). In contrast, large-scale turbulence mainly represents a parametric and an external excitation for the dynamic system (Lindner, 1992; Abdel-Rohman, 2001; Luongo and Zulli, 2011; Piccardo and Tubino, 2011; among others).

As for the galloping instability of rectangular cylinders in turbulent flow, Novak and Davenport (1970) and Laneville and Parkinson (1971) concluded that the quasi-steady theory still applies provided that the lateral force coefficient is measured in the same turbulent conditions. For a square cylinder, turbulence was found to impair the regularity of the oscillation, but to only slightly reduce the amplitude of the motion. Nevertheless, a more complicated and non-monotonic effect of turbulence on the galloping behavior of a square prism was observed in Miyata et al. (1983) and Bearman et al. (1987). Kwok and Melbourne (1980) registered large vibration amplitudes for a square-sectioned tower in turbulent flow. It is also worth noting that Laneville and Parkinson (1971) did not find any significant effect of turbulence length scale, although they pointed out that the investigated range of scales was always comparable with the body section dimensions. For short-side-ratio rectangular cylinders (having the broad face perpendicular to the flow), turbulence is known to transform hard galloping oscillators into soft ones, for which sustained vibrations arise spontaneously from rest (Novak and Davenport, 1970; Novak, 1972; Novak and Tanaka, 1974; Nakamura and Tomonari, 1977). In contrast, concerning longer-side-ratio three-dimensional prisms (having the short side facing the flow), the results reported in Novak and Davenport (1970) and Novak (1972) suggest that turbulence attenuates the galloping oscillation amplitudes until the structure becomes stable in a high turbulence flow. Nevertheless, such a stable behavior is not confirmed by the measurements reported in Miyata et al. (1983) for a two-dimensional cylinder. Indeed, the data presented in Novak and Tanaka (1974) for a rectangular prism with a side ratio of 1.5 confirm that a key role on the galloping behavior in turbulent flow is played by the aspect ratio of three-dimensional prisms. The galloping vibrations of a square-section tower were also studied in Parkinson and Sullivan (1979), where the applicability of the quasi-steady theory sufficiently away from the vortex-resonance region was ascertained. Generally speaking, from a careful analysis of the literature one can infer that the experimental work done so far on the galloping behavior in turbulent flow of rectangular cylinders is not conclusive, and that a systematic investigation on rectangular prisms with a side ratio slightly larger than one may be useful to clarify several issues of practical importance.

Concerning vortex-induced vibrations in turbulent flow, the most obvious effect observed in the literature is the variation of the Strouhal number and the associated shift of the lock-in response (Kobayashi et al., 1990; Marra et al., 2017; Mannini et al., 2017; among others). In contrast, Vickery (1966) observed for a stationary square cylinder the same Strouhal number as in smooth flow but a significant reduction of the root-mean-square and correlation length of the fluctuating lift force. For a circular cylinder, vortex-excitation has also been observed in highly turbulent flow (Pastò, 2008), though with slightly smaller amplitudes. A similar result has been obtained in Marra et al. (2017) for an inclined tapered bridge tower having a diamond-shaped cross section. Matsumoto et al. (1993) showed that a low free-stream turbulence can either significantly increase or reduce the VIV response depending on the cross-section geometry and on the specific mechanism of excitation. The measurements in turbulent flow carried out by Kobayashi et al. (1990) on two rectangular cylinders with side ratios of 2.5 and 5 revealed that turbulence is definitely more effective in attenuating the VIV response of the more elongated section. From a general perspective, the VIV response of bluff bodies in turbulent flow is a topic that still deserves extensive investigations.

Nevertheless, almost unexplored is the interference of VIV and galloping in turbulent flow. The only dedicated study is the one carried out by Bearman et al. (1987) on a square cylinder but, though the results are very interesting, the problem is far from being fully understood. In addition, from some of the measurements on a square cylinder reported in Miyata et al. (1983) one may learn that turbulence enhances the tendency of VIV and galloping to interfere in a certain Scruton number range. Nevertheless, specific tests are definitely required to understand the actual significance of the interference phenomenon for structures exposed to realistic wind flows.

The present work focuses on the experimental study in turbulent flow of the behavior of the rectangular cylinder with a side ratio of 1.5, for which a large number of data in smooth flow are already available, and which has been selected by the authors as an archetypal geometry to study unsteady galloping. In the next section, the set-ups employed in the wind tunnel tests are described along with the characteristics of the various incoming turbulent flows considered. Section 3 reports the data obtained through measurements on two stationary sectional models in smooth and turbulent flow. Section 4 presents the results for a spring-mounted model, which are interpreted on the basis of the insight gained from the static tests. Section 5 describes the buffeting calculations carried out for a better understanding of the dynamic responses observed in the wind tunnel. Finally, a discussion on the outcomes of the experimental campaign is proposed in Section 6.

## 2. Wind tunnel tests

### 2.1. Experimental set-ups

The tests were carried out in the open-circuit boundary-layer CRIACIV[1] wind tunnel in Prato, Italy. The test section is 2.42 m wide and 1.60 m high. Air is drawn by a motor with a nominal power of 156 kW, and the flow speed can be varied continuously up to 30 m/s. In the absence of turbulence generating devices, the free-stream turbulence intensity is about 1%.

A plywood sectional model (Model 1), 986 mm long ($L$), 116 mm wide ($B$) and 77 mm deep ($D$), was used for both static and dynamic tests (Fig. 1). To enforce bidimensional flow conditions, doubly symmetric rectangular plywood plates were provided at the model ends (450 mm × 150 mm × 4 mm). The model was placed horizontally in the wind tunnel with the short side of the section perpendicular to the flow. The blockage ratio for a null angle of attack, calculated here as the ratio of the cross-wind section dimension of the model to the height of the wind tunnel, was 4.8%.

A second sectional model made of aluminum (Model 2), 1 m long, 45 mm wide and 30 mm deep, was used for some additional static tests (Fig. 2) in order to further investigate the effect of turbulence length scale on the steady force coefficients. The prism was equipped with steel circular end plates with a radius of 150 mm and a thickness of 2 mm. The blockage ratio for a null angle of attack reduced in this case to less than 1.9%. However, since the majority of the tests in the present work were carried out with Model 1, the results presented must be intended to refer to it where no otherwise specified.

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