The role of free-stream turbulence in the galloping instability of small-side-ratio rectangular cylinders

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ABSTRACT: During a previous experimental campaign, a rectangular cylinder free to vibrate in the transverse degree of freedom showed a complicated behavior in turbulent flow. The present study aims at modelling the unsteady galloping behavior of the prism, incorporating the effect of homogeneous isotropic free-stream turbulence. Such an investigation represents a first attempt to explain some of the unclear features unveiled by the experiments. The nonlinear wake-oscillator model proposed between the 70s and 80s by Prof. Y. Tamura is adapted here to account for the unsteadiness in the oncoming flow. The results clarify that the response of the cylinder in a relatively large-scale turbulent wind cannot simply be ascribed to linear or nonlinear buffeting excitation. Rather, the unsteady contribution of vortex shedding seems to play a key role also in turbulent flow. Nevertheless, the oscillation amplitudes predicted by the model are significantly larger than in the experiments, so that a future refinement of the model is required.

KEYWORDS: Galloping, Vortex-induced vibration, Turbulent flow, Wake-oscillator model.

1 INTRODUCTION

The increased slenderness and lightness of modern engineering structures has raised the attention of researchers on possible transverse galloping instability of large constructions such as towers, super-tall buildings and long-span arches. In these cases, it is likely that galloping oscillations occur at a flow speed for which the contribution of vortex shedding is definitely non-negligible, making the classical quasi-steady theory unsuitable to calculate the structural response [1].

Furthermore, a recent experimental investigation on a rectangular cylinder with a side ratio of 1.5 (the shorter side facing the wind) has emphasized the crucial and complicated role played by oncoming turbulence [2]. In particular, small-scale turbulence is able to interfere with the separated shear layers and to alter significantly the aerodynamic behavior of the oscillating body. In contrast, large-scale turbulence is responsible for parametric and external excitations that nonlinearly interact with self-excited forces. Consequently, the integral length scale of free-stream turbulence is a key parameter affecting the response of the body.

Several features of the galloping response in turbulent flow observed in the wind tunnel tests in [2] still require to be understood and explained. In particular, in the case of turbulence with an integral length scale lower than the section dimensions of the cylinder, an evident delay of the onset of the oscillations beyond the vortex-resonance wind speed was encountered. In contrast, for a turbulent flow with an integral length scale of few times the characteristic cross-section dimension, the vibration amplitude was found to slowly increase with the wind speed. In this case, the relative importance of forcing due to turbulence and of vortex shedding is not clear. In the present work, the galloping behavior in turbulent flow of a rectangular cylinder is mathematically modelled with the aim to shed some light on the experimental results.

2 MATHEMATICAL MODEL

2.1 *Wake-oscillator model in turbulent flow*

The nonlinear wake-oscillator model proposed in [3-4] and later modified in [5] is considered here. The contribution of partially-correlated random flow velocity fluctuations is incorporated in the model's equations based on quasi-steady and strip assumptions, yielding:

$$Y'' + 2\zeta_0 Y' + Y = \frac{f}{m^*}\int_0^L \left[(U+\tilde{u}(z))^2 + \widetilde{w}^2(z)\right]\left[\vartheta(z) - \frac{Y' + \widetilde{w}(z)}{U + \tilde{u}(z)}\right]\frac{dz}{L} + \int_0^L \frac{(U+\tilde{u}(z))^2}{m^*} C_{Fy}(z)\frac{dz}{L} \quad (1)$$

$$\vartheta''(z) - 2\beta\upsilon(z)\vartheta'(z)\left(1 - \frac{4f^2}{C_{L0}^2}\vartheta^2(z)\right) + \upsilon^2(z)\vartheta(z) = \lambda Y'' + \upsilon^2(z)\frac{Y' + \widetilde{w}(z)}{U + \tilde{u}(z)} \quad (2)$$

where:

$$\upsilon(z) = \frac{\omega_s(z)}{\omega_0} = \sqrt{\left(U + \tilde{u}(z)\right)^2 + \widetilde{w}^2(z)} \cdot 2\pi \mathrm{St} \quad (3)$$

$$C_{Fy}(z) = C_{Fy}\left(\frac{Y' + \widetilde{w}(z)}{U + \tilde{u}(z)}\right) \quad (4)$$

In the previous equations, $Y = y/D$ and $\vartheta(z)$ are the dependent variables of the differential equations, denoting respectively the transverse displacement of the cylinder normalized with the cross-flow section dimension D and the rotation of the equivalent wake lamina [3-5]. $0 \leq z \leq L$ indicates the position along the axis of the cylinder, being L the spanwise extension of the body. $U = V/\omega_0 D$ is the reduced mean flow speed, while $\tilde{u} = u/\omega_0 D$ and $\widetilde{w} = w/\omega_0 D$ are the normalized longitudinal and transversal flow velocity fluctuations (Fig. 1). ω_0 and ζ_0 denote respectively the natural circular frequency and the critical damping ratio of the mechanical oscillator. ω_s is the circular frequency of vortex shedding, while St is the Strouhal number. C_{Fy} is the quasi-steady transverse force coefficient, which is a function of the instantaneous relative angle of attack (Fig. 1) and can be determined from static measurements of lift and drag coefficients [5]. m^* represents the mass ratio of the fluid-elastic system, while f, β, C_{L0}, and λ are aerodynamic parameters of the model, which can be estimated as described in [5].

Once the turbulent velocity fluctuations are digitally synthetized at a given number N of stations along the axis of the cylinder, the $N+1$ second-order ordinary differential equations can be numerically solved through an explicit Runge-Kutta method.

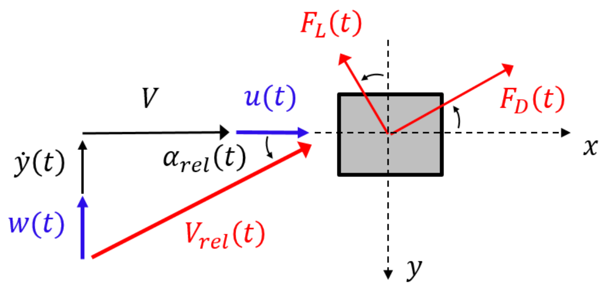

Figure 1. Schematics of flow velocities, motion components and forces.

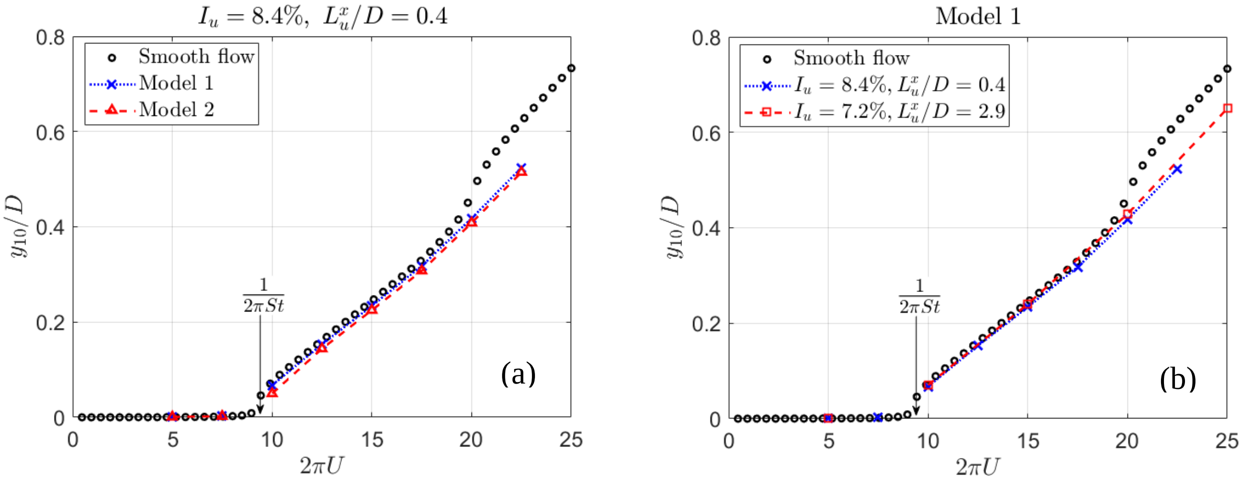

Figure 2. Comparison of wake-oscillator model results in smooth flow and in turbulent flow (a). Effect of a significant variation of integral length scale of turbulence in the equations' results. y_{10} denotes the mean of the 10%-largest oscillation maxima and minima, I_u the turbulence intensity and L_u^x the longitudinal integral length scale.

2.2 *Digital simulation of turbulent fluctuations*

The partially-correlated random field of longitudinal and transverse flow velocity fluctuations is digitally simulated as a series of cosine functions with weighted amplitudes, almost evenly spaced frequencies, and random phase angles [6]. Homogeneous isotropic turbulence has been assumed as in the reference experiments in [2]. The analytical expressions proposed in [7] for auto and cross power spectral density functions of turbulent velocity fluctuations were employed.

3 DISCUSSION OF RESULTS

The system of Eqs. (1)-(2), denoted as Model 2, was solved for some interesting test cases reported in [2]. Since such computations are expensive, a simplified version of the model is considered, in which the turbulent fluctuations are included in the mechanical oscillator equation, while only the mean velocity component is retained in the wake equation (Eq. (2)). This simplified version of the model is called Model 1. Its results are compared with those of Model 2 in Figure 2(a). Clearly, the difference between the two approaches is minimal. In the considered case, the results are also very close to those obtained in smooth flow up to a normalized oscillation amplitude of about 0.4.

Figure 2(b) compares the results obtained in two test cases with similar turbulence intensity I_u but different longitudinal integral length scale of turbulence L_u^x. It can be noticed that the model's results are nearly insensitive to a variation of L_u^x, which is in clear disagreement with experiments.

All of the previous results were obtained considering the same aerodynamic parameters as in smooth flow. Nevertheless, the transverse force coefficient is strongly affected by turbulence intensity and integral length scale (see Fig. 3(a) and results in [2]). Therefore, the equations were also solved accounting for the values of C_{Fy} measured in turbulent flow (Fig. 3(b)). The other aerodynamic parameters of the model were kept unchanged (however, it was verified that the value of C_{L0} is very similar to the one measured in smooth flow, though the lift spectrum is more broad-banded [2]). In a similar way to a linear analysis [2], the nonlinear buffeting response significantly underestimates the experimental amplitude-velocity curve. However, the nonlinear effect of turbulence is even responsible for a delay of the instability compared to the quasi-steady galloping threshold. In contrast, the wake-oscillator model correctly predicts the onset of oscillations at the Kármán-vortex resonance velocity, but it significantly overestimates the vibration amplitudes. It is also to note that the contribution of turbulence in the wake-oscillator model has a significant effect on the response only for large oscillation amplitudes.

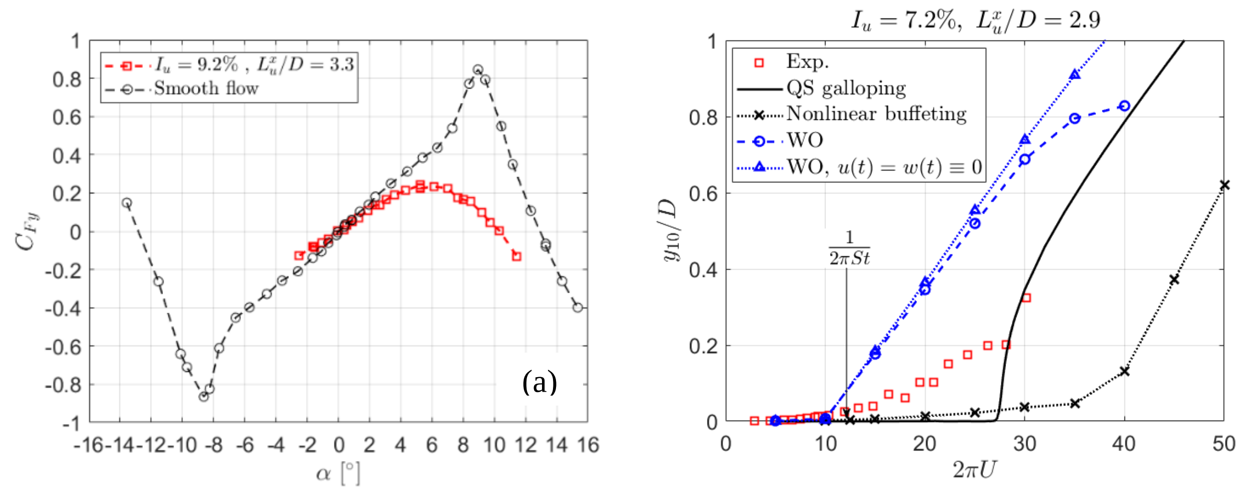

Figure 3. Transverse force coefficients measured in smooth and in turbulent flow (a). Comparison between experiments and results of wake-oscillator model (WO) calculations carried out with the values of C_{Fy} measured in turbulent flow (b). The classical quasi-steady (QS) galloping response and the results of a nonlinear buffeting calculation (obtained setting to zero the first term on the right-hand side of Eq. (1)) are also reported.

4 CONCLUDING REMARKS

The present investigation clarifies that linear and nonlinear buffeting cannot explain the response of a rectangular cylinder observed in the experiments in turbulent flow. As suggested by the wake-oscillator model results, the unsteady contribution of vortex shedding seems to play a key role even for a highly turbulent oncoming flow. However, the model significantly overestimates the vibration amplitudes. This may be ascribed to the values of the aerodynamic parameters f, β and λ, which may assume significantly different values in turbulent flow. In addition, the contribution of turbulence was incorporated in the equations according to a quasi-steady scheme, whereas it may be significantly unsteady. All of these issues need to be carefully addressed in the future.

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