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Numerical investigation of transverse galloping in turbulent flow

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Abstract

This paper attempts to model the complicated effects of incoming turbulence on the unsteady galloping instability of a rectangular cylinder, which arises due to the interference of vortex-induced vibration and quasi-steady galloping. As a first step, a purely quasi-steady nonlinear model is considered. Then, a modified version of the nonlinear wake-oscillator model proposed between the 70's and the 80's by Prof. Y. Tamura is considered. In both cases, turbulence is included in the model by synthetizing a random field of partially-correlated flow velocity fluctuations.

1 Introduction

Slender bluff bodies immersed in an airstream and allowed to vibrate in the transverse degree of freedom can be prone to vortex-induced vibration (VIV) and galloping. If the mass-damping parameter is sufficiently low, the ranges of excitation of the two phenomena tend to approach, and a peculiar type of instability occurs, which one may call "unsteady galloping". In this case, large amplitude of vibration are exhibited in a range of flow speed where no excitation is predicted by the classical theories of VIV and galloping (Mannini et al., 2014). This phenomenon was shown to be an issue for rectangular cylinders with a cross-sectional side ratio close to one.

While the main characteristics of unsteady galloping are now fairly clear in smooth flow (Mannini et al., 2016, 2018a), a recent experimental wind tunnel campaign in various turbulent flows underscored a complicated behaviour of a rectangular cylinder with a side ratio of 1.5. In particular, several features still need to be understood, such as the progressive delay of the instability onset beyond the vortex-resonance flow velocity (Mannini et al., 2018b). Free-stream turbulence also seems to be able to interact in a nonlinear way with the unsteady wake and with the quasi-steady wake undulations, transferring energy from the vortex shedding frequency to the natural frequency, thereby promoting the onset of sustained vibrations at flow speeds significantly lower than the quasi-steady galloping threshold.

In the present work, the effect of turbulence on the galloping instability of a rectangular cylinder is studied through numerical analyses, focusing on the unsteady features of the phenomenon.

2 Quasi-steady approach

As a first step, the contribution of turbulence is included in a purely quasi-steady nonlinear model, where the transverse force per unit length at the spanwise station z can be expressed as:

$$F_y(z,t)=\frac{1}{2}\rho\left[V+u(t)\right]^2 DC_{Fy}(\alpha) \tag{1}$$

$$C_{Fy}(\alpha)=-\sec(\alpha)\left[C_L(\alpha)+C_D(\alpha)\tan(\alpha)\right] \tag{2}$$

$$\alpha(t)=\operatorname{atan}\left[\frac{w(t)+\dot{y}}{V+u(t)}\right] \tag{3}$$

where ρ is the air density, D the cross-wind section dimension of the cylinder; V the mean wind speed, $u(t)$ and $w(t)$ the longitudinal and vertical turbulent velocity fluctuations respectively; α the apparent angle of attack; C_L, C_D and C_{Fy} the lift, drag and transverse force coefficients respectively; y denotes the transverse direction, and the overdot the derivative with respect to time t.

A partially correlated vectorial random field of velocity fluctuations is synthetized following the Weighted-Amplitude Wave Superposition method, and time-domain calculations are performed. The first results show the tendency of the unsteady flow to mitigate the galloping instability, in a way that has not been observed in the experiments indeed.

3 Nonlinear wake-oscillator model

In a second step, the contribution of turbulence is considered in a nonlinear wake-oscillator model, originally proposed by Tamura and Matsui (1979) for a two-dimensional circular cylinder, then extended to the case of an elastic continuous beam by Tamura and Amano (1983), and finally applied to the case of an elastically-suspended rigid square cylinder by Tamura and Shimada (1987). The modified version of such a model has recently been proved to capture the main features of the interference of VIV and galloping in a smooth airflow (Mannini et al., 2018a). An appealing feature of this model is the fact that it is built on some physical bases, and consequently all the parameters have a clear physical meaning.

Once again, turbulence is included in the nonlinear differential equations of the model according to a quasi-steady perspective, employing the synthetic random field of partially-correlated flow velocity fluctuations. The steady force coefficients measured both in smooth and in turbulent flow are employed. The roles of external and parametric excitation are emphasized.

The first results reveal that the model is able to predict a reduction of the oscillation amplitude due to incoming turbulence. Nevertheless, it does not seem able to explain the delay of the instability onset observed in the experiments in turbulent flow.

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