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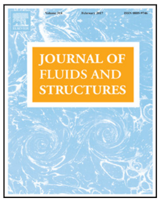

Experimental study on the flutter-induced motion of two-degree-of-freedom plates

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HIGHLIGHTS

- A specific aeroelastic setup developed for the large-amplitude motion.
- The main features of excitation mechanism and incipient motion are discussed.
- Effects of the dynamical parameters in the post-critical motion.
- High heaving-damping ratios and a damping-induced destabilisation.

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ABSTRACT

This work investigates the flow-induced motion originating from the classical-flutter instability, and it is motivated by energy-harvesting applications. The influence of several sets of dynamic parameters is studied, improving the scientific understanding of the large-amplitude response and guiding the design of more unstable configurations. Wind-tunnel tests were conducted on elastically-suspended rigid models with an elongated rectangular cross section, undergoing a two-degree-of-freedom motion with transverse (heaving) and rotational (pitching) components. The aeroelastic setup was specifically developed to allow for a large-amplitude motion (about one chord in heaving and more than 90°in pitching) and to simulate an energy-conversion apparatus by increasing the heaving damping (up to about 18% of the critical one) through eddy-current dampers. After a sub-critical bifurcation, large limit-cycle oscillations were recorded, with steady-state amplitudes increasing with the flow speed. For some configurations, a low-amplitude response was also observed around the instability threshold. It was found that a small mass unbalance aft of the elastic axis significantly fosters the system instability and affects the heaving and pitching motion amplitudes. The latter are also markedly influenced by the still-air frequency ratio. In the presence of high values of the heaving damping, the post-critical amplitude is usually reduced, although a destabilising effect of damping was observed in some specific cases. Finally, the motion is magnified for lower-inertia systems.

1. Introduction

The flow-induced excitation mechanism responsible for the two-degree-of-freedom (2-DoF) classical-flutter instability relies on a fluid-elastic modal coupling in attached-flow conditions, which involves transverse (heaving) and rotational (pitching) motion components, and is well known in the literature (*e.g.* Fung, 2008). In aeronautical, civil and mechanical

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engineering, structural systems are usually designed to warrant a safety margin respect to the onset of this violent phenomenon. Thus, only few research studies go one step further debating the response of the system in the large-amplitude post-critical regime of oscillation (*e.g.* Lee et al., 1999; Dowell and Tang, 2002).

From a different perspective, flutter-induced vibrations can be an effective source of useable power when the system is equipped with a kinetic-energy-conversion apparatus (Roundy, 2005) and is specifically designed to perform steady-state motion (see the review papers of Xiao and Zhu (2014) and Young et al. (2014) about flapping-foil systems with controlled motion, and the works of Peng and Zhu, 2009; Bryant and Garcia, 2011; Dias et al., 2013; Pigolotti et al., 2017b among others about fluttering systems with spontaneous motion). The exploitation of 2-DoF fluttering devices for propulsion, thus reversing the energy transfer, has also been considered (Young et al., 2007; Matsumoto, 2013). In both cases, the scientific understanding of the flutter-induced motion becomes of fundamental importance.

In a first approximation, additional mechanical damping can simulate the presence of an energy-conversion apparatus (Karami and Inman, 2011), thus the damping plays a key role in the fluid–structure interaction mechanism of energy harvesters. In the case of generators exploiting classical flutter, the conversion apparatus acts in the heaving motion component, since the system is less affected by disturbances on that DoF and the energy extraction is more efficient (Matsumoto et al., 2006). Consequently, unusual high values of the heaving damping can be envisaged in energy-harvesting applications of flutter, and this issue has not been sufficiently studied yet.

Moreover, the enhancement of the generator performance requires the understanding of the way to conceive more unstable systems (Pigolotti et al., 2017b), anticipating the critical flow speed and promoting large amplitudes of vibration. Therefore, the flutter problem has to be dealt with exactly in the opposite way compared to traditional engineering applications. In particular, the knowledge of the system response in the critical and post-critical regime with respect to the governing dynamic parameters is a fundamental issue that has to be clarified.

The post-critical response due to the classical-flutter instability was faced in pioneering works (*e.g.* McIntosh Jr et al., 1981; Yang and Zhao, 1988) and is still being debated (*e.g.* Amandolese et al., 2013; Pereira et al., 2015; Amandolese, 2016; Pigolotti et al., 2017b). Nevertheless, a comprehensive understanding of the phenomenon has not been achieved yet. Moreover, in most cases the studies refer to systems with mechanical nonlinearities whose effects blend with those of the aerodynamic nonlinearities (*e.g.* Yang and Zhao, 1988; Ko et al., 1998; Sousa et al., 2011; Abdelkefi et al., 2012; Abdelkefi and Hajj, 2013), or the excursion in the post-critical field had to be contained due to the technical limits of the setup (*e.g.* Schewe et al., 2003; Sousa et al., 2011; Král et al., 2014; Pereira et al., 2015). Also, the effects on the post-critical response of the parameters governing the linearised problem are not clear, being the two regimes governed by different flow-induced excitation mechanisms. In fact, when the amplitude of oscillation becomes large, massive flow separation significantly contributes to produce nonlinear aerodynamic loads, and the dynamic stall plays a major role in the establishment of a limit-cycle oscillation (LCO).

Although the amplitude–velocity curves usually show a rather simple shape (*e.g.* Amandolese et al., 2013; Pigolotti et al., 2017a, b), reliable analytical nonlinear models of self-excited loads are not available yet. The problem can be preliminary circumvented by extending to the post-critical regime the unsteady aeroelastic loads derived from the potential-flow linear theory (*e.g.* Emory, 2010; Pereira et al., 2015), then also applying the harmonic balance method to investigate the LCO characteristics (*e.g.* Yang and Zhao, 1988; Shahrzad and Mahzoon, 2002). In addition, quasi-steady approaches involving dynamic-stall models (*e.g.* Emory, 2010; Abdelkefi et al., 2012) or the fitting of experimental steady forces (*e.g.* Shahrzad and Mahzoon, 2002; Arena et al., 2015) can approximate such a behaviour analytically; linear quasi-steady models (Fung, 2008) are used for systems having structural nonlinearities (*e.g.* Strganac et al., 2000; Emory, 2010). Differently, the potential-flow theory by Lighthill (1971) can be used to predict the oscillatory behaviour of elongated flexible bodies in an axial flow (*e.g.* in Michelin and Doaré, 2013 for a cantilever flag). Nevertheless, as noted by Lighthill himself, such a theory is not applicable in the case of a two-dimensional thin plate or aerofoil. Semi-empirical approaches can also be adopted (*e.g.* the ONERA model of Petot, 1989, as applied in Fragiskatos, 1999 and Malher et al., 2017), but specific tests are required to calibrate the model parameters. On the other hand, computational (*e.g.* Dowell and Hall, 2001; de C. Henshaw et al., 2007; Peng and Zhu, 2009) and experimental (*e.g.* Amandolese et al., 2013; Malher et al., 2017; Pigolotti et al., 2017a, b) approaches are more effective, but the large-amplitude motion in both DoFs complicates the design of both setups.

The goal of the present research work is to study experimentally and in a systematic way the flutter-induced motion of a 2-DoF sectional model of a flat plate. A specific wind-tunnel setup was designed to allow for very-large-amplitude, coupled and uncoupled, motions (up to a model-chord length in heaving and more than 90° in pitching) and high heaving-damping levels (critical damping ratios up to 18%). A wide range of configurations were considered, governed by sets of parameters that have never been investigated so far (especially the high values of damping), but that are of interest for energy-harvesting applications. Therefore, the scientific understanding of the flutter phenomenon is also improved.

The paper is organised as follows. Section 2 reports the linear analytical approach, highlighting the choice of the range of variation of the governing parameters, whereas Section 3 provides a detailed description of the aeroelastic setup. The results about the critical condition are presented in Section 4, and Section 5 discusses the main results about the post-critical response, pointing out the influence of several governing parameters.