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Flutter of spring-mounted flexible plates in uniform flow

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ABSTRACT

A fluid–structure interaction (FSI) system is studied wherein a cantilevered flexible plate aligned with a uniform flow has its upstream end attached to a spring mounting. This allows the entire system to oscillate in a direction perpendicular to that of the flow as a result of the mounting's dynamic interaction with the flow-induced oscillations, or flutter, of the flexible plate. We also study a hinged-free rotational-spring attachment as a comparison for the heaving system. This variation on classical plate flutter is motivated by its potential as an energy-harvesting system in which the reciprocating motion of the support system would be tapped for energy production. We formulate and deploy a hybrid of theoretical and computational modelling for the two systems and comprehensively map out their linear-stability characteristics at low mass ratio. Relative to a fixed cantilever, the introduction of the dynamic support in both systems yields lower flutter-onset flow speeds; this is desirable for energy-harvesting applications. We further study the effect of adding an inlet surface upstream of the mount as a means of changing the destabilising mechanism from single-mode flutter to modal-coalescence flutter which is a more powerful instability more suited to energy harvesting. This strategy is seen to be effective in the heaving system. However, divergence occurs in the rotational system for low spring natural frequencies and this would lead to its failure for energy production. Finally, we determine the power-output characteristics for both systems by introducing dashpot damping at the mount. The introduction of damping increases the critical speeds and its variation permits optimal values to be found that maximise the power output for each system. The addition of an inlet surface is then shown to increase significantly the power output of the heaving system whereas this design strategy is not equally beneficial for the rotational system.

1. Introduction

This paper reports upon the Fluid–structure Interaction (FSI) of thin cantilevered flexible plates in a uniform axial flow with the novel introduction of a spring mounting system that additionally permits the entire system to oscillate in the direction perpendicular to the flow. The system may include a rigid inlet surface upstream of and fixed to the cantilever and both a damper and an added mass that can additionally be used to modify the dynamics of the support mechanism. A schematic of the two-dimensional system studied is depicted in Fig. 1(a). This system bears similarities to that of Kheiri et al. (2014) who modelled spring-mounted end conditions for one-dimensional plug flow through a flexible tube. The key dynamics of the new system are contrasted with the reference system of a hinged-free plate mounted on a rotational spring at the leading edge as shown in Fig. 1(b); this latter system

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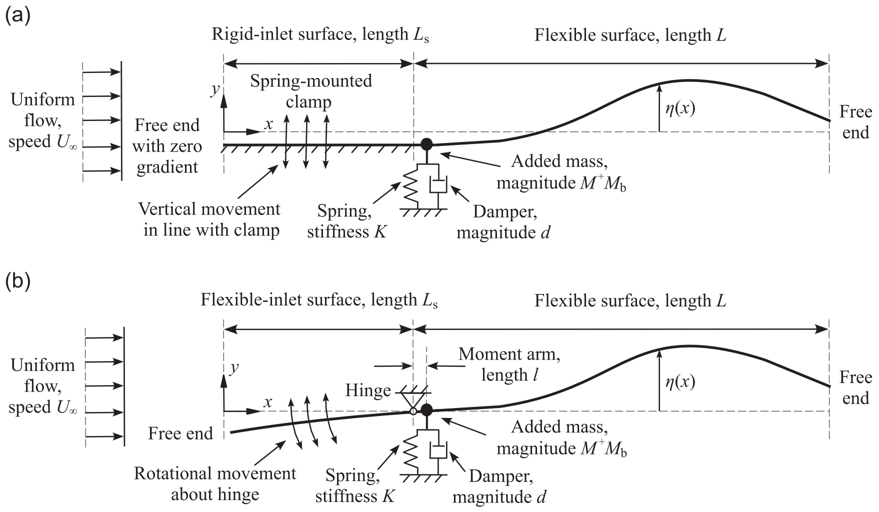

Fig. 1. Schematics of the spring–mass mounted flexible plates embedded in a uniform flow: (a) clamped-free plate; (b) free-hinged-free plate.

has recently been studied by Singh et al. (2012a) and Chad Gibbs et al. (2012) but we make the addition of an extended inlet upstream of the hinge by enforcing a boundary condition detailed in Pitman and Lucey (2009). This comparison allows us to identify the key differences between a shear-force driven mounting system and that driven by bending moment, these terms referring to the systems depicted in Fig. 1(a) and (b) respectively. To give a complete picture of the behaviour of these systems, key results are also compared to those of the fixed cantilever system presented in Howell et al. (2009).

While the present system is of fundamental interest its dynamics may be relevant to many physical systems that involve a fluttering-flag/flexible-plate type of behaviour. Importantly, we note that understanding this system may further elucidate the snoring phenomenon, capturing the dynamics of the fluttering uvula mounted on the flexible yet constrained soft palate; see Elliott et al. (2011). However, the main goal of the present work is the assessment of the potential of the vertical-clamped-free flexible plate as an energy-harvesting device. An early reference to the ample physical power present in the flutter instability was Thoma (1939) who observed how the fluttering of a ship's sail made the whole boat shake. In the system presented herein this fluid kinetic energy is extracted through its transfer to the flexible plate in a process of controlled aero-/hydro-elastic destabilisation that then drives the reciprocating motion of the mounting system from which power can be extracted. Many of the applications and concepts that have been proposed for such *flutter power* devices are summarised in Elvin and Erturk (2013). Recent interest in flutter has also been seen in the field of micro-/nano-technology – for examples see Matin et al. (2013) and Parkin and Hähner (2013) – where energy harvesting devices of this type could find useful application. We shall expand on the topic of flutter energy harvesting in a later section.

We first summarise studies of the fixed-cantilever system to date. The study of Kornecki et al. (1976) was the first to conduct comprehensive modelling and analysis of the fixed cantilever case, although it has classical roots that date back to Lord Rayleigh. Using ideal flow Kornecki et al. studied the two-dimensional problem of a flexible plate embedded in an infinite domain of fluid, as did the more recent work of Huang (1995), Yamaguchi et al. (2000), Watanabe et al. (2002), Argentina and Mahadevan (2005) and Tang and Paidoussis (2007). The effects of finite aspect ratio were incorporated in Eloy et al. (2007, 2008), while in Doaré et al. (2011) finite spanwise containment effects in a duct were considered, showing that these principally served as a correction to the essentially two-dimensional dynamics of the flutter of flexible plates. The three-dimensional, non-linear problem has recently been studied theoretically and experimentally in Zhao et al. (2012). The flow-plate configuration has been extended to that of a flexible plate mounted in plane-channel flow; see Aurégan and Depollier (1995) and Guo and Paidoussis (2000). All of these studies predict that the plate loses its stability through flutter that sets in beyond a critical uniform flow speed or Reynolds number in the case of viscous channel flow; for the latter refinements see Balint and Lucey (2005), Tetlow and Lucey (2009) and Elliott et al. (2011). For short plates the flutter mode is predicted to comprise mainly a combination of the first and second *in vacuo* modes. The interaction of these two modes in the energy-transfer process that destabilises the flexible plate has recently been explained by Huang and Zhang (2013). For long plates, or plates with heavy fluid loading, the critical mode is dominated by higher-order mode content. Howell et al. (2009) elucidated the instability mechanisms showing that 'short' plates – those with low mass-ratio – succumb to single-mode flutter (smf) while 'long' plates – those with high mass-ratio – are destabilised by modal-coalescence (mc) flutter of the Kelvin–Helmholtz-resonance type predicted exactly for fluid-loaded plates of infinite extent and discussed, for example, in Crighton and Oswell (1991) and Lucey (1998). Howell et al. (2009) also showed that the introduction of a rigid inlet plate upstream of the cantilever connection promoted the modal-coalescence type of flutter which is a more severe instability than single-mode flutter. For energy-harvesting applications its realisation would be advantageous and therefore in this paper we consider spring-mounted flexible plates both with and without a (moving) upstream plate.