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Stability of a flexible insert in one wall of an inviscid channel flow

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ABSTRACT

A hybrid of computational and theoretical methods is extended and used to investigate the instabilities of a flexible surface inserted into one wall of an otherwise rigid channel conveying an inviscid flow. The computational aspects of the modelling combine finite-difference and boundary-element methods for structural and fluid elements respectively. The resulting equations are coupled in state-space form to yield an eigenvalue problem for the fluid–structure system. In tandem, the governing equations are solved to yield an analytical solution applicable to inserts of infinite length as an approximation for modes of deformation that are very much shorter than the overall length of the insert. A comprehensive investigation of different types of inserts – elastic plate, damped flexible plate, tensioned membrane and spring-backed flexible plate – is conducted and the effect of the proximity of the upper channel wall on stability characteristics is quantified. Results show that the presence of the upper-channel wall does not significantly modify the solution morphology that characterises the corresponding open-flow configuration, i.e. in the absence of the rigid upper channel wall. However, decreasing the channel height is shown to have a very significant effect on instability-onset flow speeds and flutter frequencies, both of which are reduced. The channel height above which channel-confinement effects are negligible is shown to be of the order of the wavelength of the critical mode at instability onset. For spring-backed flexible plates the wavelength of the critical mode is much shorter than the insert length and we show very good agreement between the predictions of the analytical and the state-space solutions developed in this paper. The small discrepancies that do exist are shown to be caused by an amplitude modulation of the critical mode on an insert of finite length that is unaccounted for in the travelling-wave assumption of the analytical model. Overall, the key contribution of this paper is the quantification of the stability bounds of a fundamental fluid–structure interaction (FSI) system which has hitherto remained largely unexplored.

1. Introduction

This paper describes the modelling and prediction of the flow-induced instabilities experienced by a finite flexible wall inserted in one side of an otherwise rigid-walled two-dimensional channel conveying a fluid flow; the system studied is depicted in Fig. 1. We assume a potential flow thereby making the results relevant to flows with very high (effectively

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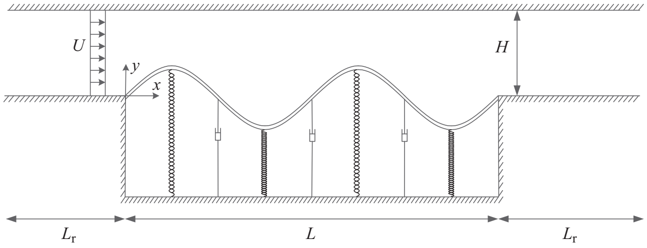

Fig. 1. Schematic of the fluid–structure interaction system studied; in this illustration the insert comprises a spring-backed flexible plate (compliant wall).

infinite) Reynolds number that would be typically encountered in engineered systems as opposed to the biomechanical applications that usually motivate study of the system in Fig. 1. However, there remain some biomechanical applications for which the present findings may be useful; these are discussed below. The system studied is also related to that of fluid-conveying pipes for which there exists a rich literature motivated by many industrial applications such as those found in process engineering. Accordingly, the present system may be considered to sit at the intersection of a number of well-studied fundamental problems that we briefly review in this introduction. The overarching purpose of this paper is to characterise the fundamental fluid–structure interaction (FSI) of a system that has hitherto received very little attention when the flow, in practical terms, may be considered inviscid.

In the absence of the upper channel wall in Fig. 1, the system is immediately recognised as the classical problem of panel flutter first studied for aeronautical applications (Bisplinghoff et al., 1955; Dugundji et al., 1963). In marine environments, studies of compliant walls or flexible panels were motivated by the experiments of Kramer (1960) that suggested that wall compliance could reduce skin-friction by delaying boundary-layer laminar-to-turbulent transition; for examples, see Carpenter and Garrad (1985) and Carpenter et al. (2000). Other applications, such as unstable vibrations of steel (flexible) plates of spillways in hydro-power plants and hull panels of modern high-speed ships, have continued to motivate studies of the fundamental system. Therefore, a variety of methods have been developed for this problem. Early studies, such as those of Weaver and Unny (1970) and Kornecki et al. (1976) used a Galerkin approach to predict instabilities, whereas Carpenter and Garrad (1986) used a travelling-wave approach, and numerical simulations were performed by Lucey and Carpenter (1992). Recently, Pitman and Lucey (2009) presented a versatile method by which system eigenvalues can be directly extracted even for structurally inhomogeneous systems. The broad consensus of these linear studies for incompressible, inviscid flow is that a flexible panel or compliant wall first loses its stability to divergence, while at higher speeds divergence recovery may occur, but at sufficiently high flow speeds a modal-coalescence type of flutter dominates the system response.

The aforementioned analytical solution methods are based upon a normal-mode decomposition of system disturbances. The Galerkin approach constructs a system solution as the sum of a set of discrete orthogonal functions usually chosen as the in vacuo structural modes because they each automatically satisfy the boundary conditions of the structural side of the system. For walls of infinite length, the travelling-wave assumption invokes a continuous spectrum of locally defined normal modes to characterise system disturbances. The ensuing solutions then predict instability in the limit of infinite time; i.e. as a boundary-value problem, in the form of the most unstable system eigenmode. However, recent work shows that this is not necessarily the route to large-amplitude deformations. Schmid and de Langre (2003) and Coppola and de Luca (2010) demonstrated theoretically that very significant transient growth of perturbations can occur through the non-normality of the system equations. Theoretical predictions of this type of phenomenon were confirmed in the experimental studies of Hémon et al. (2006) and Schwartz et al. (2009). The theoretical framework established in these non-modal analyses maximises the time-evolution of an energy norm for the fluid–structure system as an envelope over all potential initial states. This captures the growth of disturbances that can bypass conventional linear-instability mechanisms to reach finite amplitudes which may occur for system control parameters (e.g. the flow speed) below the critical values based on a modal analysis. This line of investigation is not pursued in the present paper although the methods we deploy are amenable to this type of study. Thus, for example, Tsigklifis and Lucey (2013) have recently extended the modelling of Pitman and Lucey (2009), upon which the present analysis is based, to analyse non-modal transient growth in boundary-layer flow over a compliant panel.

With a flexible insert comprising the wall of a channel, the present work bears similarity with studies of fluid conveying flexible pipes. Pipe-buckling (divergence) and flutter have been predicted at sufficiently high flow speeds, for example, by de Langre and Ouvrard (1999) and Doaré and de Langre (2002), in an infinitely long pipe comprising parallel flexible surfaces in the undeformed state. In many of these studies, a one-dimensional (or plug) flow is assumed in which the flow follows the curve of the deformed channel (or pipe) via the Païdoussis (1998, 2003) equation. Of closer similarity to the present work that features flow curvature varying across the channel (the y-direction in Fig. 1) is the study of Weaver and Païdoussis (1977) that modelled two-dimensional potential flow in an infinitely long flexible channel using a travelling-wave assumption of disturbances in the streamwise direction and a Galerkin approach for a finite section of the channel. They found that (i) when the walls display sinuous behaviour, divergence-onset flow speed increases as the channel height decreases; and (ii) when the walls display varicose behaviour, divergence-onset flow speed decreases as the channel height decreases. The first can be explained by the decrease in destabilising centrifugal force for a reduced mass of fluid traversing