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Aero-/hydro-elastic stability of flexible panels: Prediction and control using localised spring support

B.H. Tan, A.D. Lucey*, R.M. Howell

Fluid Dynamics Research Group, Curtin University of Technology, P.O. Box U1987, Perth 6845, Australia

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ABSTRACT

We study the effect of adding localised stiffness, via a spring support, on the stability of flexible panels subjected to axial uniform incompressible flow. Applications are considered that range from the hydro-elasticity of hull panels of high-speed ships to the aero-elasticity of glass panels in the curtain walls of high-rise buildings in very strong winds. A two-dimensional linear analysis is conducted using a hybrid of theoretical and computational methods that calculates the system eigen-states but can also be used to capture the transient behaviour that precedes these. We show that localised stiffening is a very effective means to increase the divergence-onset flow speed in both hydro- and aero-elastic applications. It is most effective when located at the mid-chord of the panel and there exists an optimum value of added stiffness beyond which further increases to the divergence-onset flow speed do not occur. For aero-elastic applications, localised stiffening can be used to replace the more destructive flutter instability that follows divergence at higher flow speeds by an extended range of divergence. The difference in eigen-solution morphology between aero- and hydro-elastic applications is highlighted, showing that for the former coalescence of two non-oscillatory divergence modes is the mechanism for flutter onset. This variation in solution morphology is mapped out in terms of a non-dimensional mass ratio. Finally, we present a short discussion of the applicability of the stabilisation strategy in a full three-dimensional system.

1. Introduction

This paper addresses and extends the classical fluid–structure interaction (FSI) problem wherein a flexible plate is destabilised by the action of a fluid flow parallel to the undisturbed panel. The modern capabilities of high-speed ships with cruise speeds in the range of 38–45 knots (19.5–23.1 m/s) – and up to 60 knots (30.1 m/s) when powered by gas-turbine engines – mean that hydroelastic instability increasingly needs to be accounted for in the design of hull panels. Recent architectural designs have seen the introduction of curtain walls comprising glass or perspex panels as an outer skin on high-rise buildings for a combination of aesthetic and passive temperature-control reasons. In addition to normal-loading effects, these may be susceptible to aeroelastic instability in storm or hurricane-force winds aligned with the main axis of the panel. In this paper we present an analytical study of panel stability into which localised stiffening is added and used to control aero-/hydro-elastic instability in the above and other applications of the basic configuration.

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* Corresponding author. Tel.: +61 8 9266 7048; fax: +61 8 9266 2681.
E-mail address: A.Lucey@curtin.edu.au (A.D. Lucey).

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The high Reynolds-number regime typical of the types of engineering applications cited above makes the neglect of viscous effects on the flow a good approximation. Accordingly, potential flow is most often assumed as is the case in this study. Given the importance and ubiquity of applications, this FSI system has generated a rich literature in which, most commonly, a Galerkin method is used to predict the system response with a particular focus on the parameters for which it becomes unstable. Thus, for example, [1–5] show that as the flow speed is increased for a given flexible plate, the panel first loses its stability to divergence. This buckling type of instability occurs because the fluid forces generated by a deformation exceed the restorative structural forces of that deformation. For a simple flexible plate held at both its ends, the fundamental mode is the critical mode for divergence. If the flow speed is increased further, divergence is replaced by modal-coalescence flutter that is best characterised as a Kelvin–Helmholtz type of resonance.

In parallel to these types of study, flexible compliant walls of infinite extent comprising more than one structural component (*e.g.* a spring-backed flexible plate) have been studied, *e.g.* [1,6,7] using an analytical approach wherein all system perturbations take a travelling-wave form, for example $\exp[i(\alpha x - \omega t)]$ wherein α and ω are respectively the perturbation wavenumber and angular frequency. The omission of end effects – that may be considered to be inhomogeneities in such modelling – is broadly acceptable provided that the length of the panel in any application is much longer than the wavelength of the critical modes being studied. However, under such conditions the travelling-wave analysis requires that some structural damping is present for the realisation of divergence instability although its predictions of divergence-onset flow speed agree with those of the Galerkin approach. This discrepancy was addressed in [8] wherein the role of end conditions, even for very long flexible walls was explained. More recently the rigorous analysis of [9] constructed a travelling-wave model that incorporated the fixed wall ends through a Weiner–Hopf technique and thereby reconciled the differences in findings between the two types of modelling.

Clearly, the aforementioned boundary-value studies predict the long-time response of the system after transients from some form of initial excitation have either been attenuated or convected away. The finite-time response can be of equal importance in that it links the original source and characteristics of an initial deformation to the long-time response through a process of response evolution. The ability to model the finite-time, or receptivity, problem may lead to engineering strategies that interrupt or modify this evolution and thereby prevent or postpone panel instability. Studies of system response to a source of initial or continuing localised excitation have been presented. For example, [10,11] respectively used initial impulse and oscillatory line excitation for the present system, while [12] tackled the closely related shell problem with oscillatory line excitation. Using a different analytical approach, [13] showed that absolute instability – that aligns with divergence – could exist in the system if structural damping were included. These analyses assumed an infinitely long flexible panel and focused on the long-time response. Nevertheless, they showed that the system could support a remarkable range of FSI wave types. Using numerical simulation, [14] showed that the effects of finiteness and transients led to globally unstable responses unseen in the analyses of infinitely long elastic panels.

In the present work, we use the hybrid of theoretical and computational modelling presented in [15] that casts the FSI system equation in state-space form after solving the coupled fluid and structure equations using boundary-element and finite-difference methods respectively. Like the purely analytical models discussed above, this approach is used to compute the system eigenmodes while its numerical-simulation aspects readily accommodate inhomogeneity in the base system. Thus we can evaluate the effect of an added localised spring support on the system eigenmodes with a particular focus on instability-onset flow speeds. We also extend the modelling of [15] in order to solve the initial-value problem and thereby simulate the transient response of finite flexible panels showing how its evolution from a source of initial excitation evolves into the infinite-time eigenmodes predicted by the boundary-value approach.

The paper is laid out as follows: We first extend the FSI system model of [15] to permit the inclusion of impulse line excitation and a supporting spring foundation that may either be uniform or comprise a discrete spring at a point along the flexible plate. We then present three sets of results that illustrate the system dynamics covering a range of applications. The first concerns a homogeneous Kramer-type compliant wall [7] comprising a flexible plate with a uniformly distributed spring foundation. In part, we use this case to validate the present modelling and its implementation. The second set of results addresses the classical case of a simple metal flexible panel subjected to water flow for which we show how the addition of a spring support can be used to modify hydroelastic instability onset. This case typifies the vast majority of incompressible flow studies for which the fluid-to-solid ratio is $O(1)$. In the third set of results we consider airflow over a glass or aluminium panel for which the fluid-to-solid ratio is $O(10^{-3})$, giving a system that has not hitherto been fully explored, presumably due to a lack of recognised applications until the emergence of curtain walls as an architectural feature. We show that this regime possesses some very different dynamics from the classical hydro-elastic case. We therefore map out the parameter space over which the differences occur as well as showing how adding a spring support can modify both divergence onset and the flutter characteristics in air-over-glass aero-elastic applications. Finally we unify our findings in the conclusions and explain how the present two-dimensional strategy for controlling aero-/hydro-elastic instability of panels can be carried across to real three-dimensional applications.

2. Methods

We first summarise the well-known governing equations for the fluid–structure systems depicted in Fig. 1. We then outline the hybrid theoretical–computational approach that permits either an eigen-analysis to be conducted for the