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The hydroelastic destabilisation of finite compliant panels

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1. Introduction

The interactive dynamics of a flexible panel and an external fluid flow underpins a great variety of technological applications. When the panel comprises the skin of an aircraft or ship, instability of the panel, fed by the transfer of fluid kinetic energy to the structure, is highly undesirable; for example see [1,2]. However, the motion of a flexible boundary can also yield beneficial effects such as skin-friction drag reduction through the postponement of boundary-layer transition; for example see [3]. This paper focuses on the evolution of linear instability of a flexible panel in the presence of a uniform flow. The assumption of uniform flow renders the study applicable to the fluid-loading effects of turbulent boundary-layer flows wherein flow shear is principally confined to a very thin layer adjacent to the wall. However, it also approximates laminar boundary-layer flows when the boundary-layer thickness is small in comparison to the wavelength of the panel deformation. Seminal studies of this fundamental problem, for example [1,2,4], took a boundary-value approach, mapping out the instability boundaries associated with divergence and flutter. Attention later turned to the question of how the hitherto assumed system disturbances might come into being. Thus, in [5,6] line-excitation was introduced to initiate disturbances and the resulting system studied as a proper initial-value, boundary-value, problem. This approach revealed the very subtle complexities of the wave-bearing system identifying a vast range of waves each distinguished by their combination of phase speed, group velocity, energy flux and activation energy, being positive/negative-energy or Kelvin-Helmholtz type waves. These studies considered an unsupported, thin, elastic plate of infinite extent. Governed by a single control parameter, the non-dimensional flow speed, a critical velocity for absolute instability, associated with a triple point in the complex wavenumber plane, was identified. At flow speeds lower than critical a single downstream-propagating convective instability was predicted. The absolute and convective instability boundaries for a range of related flow-structure systems have been mapped in [7] and recently it has been shown [8] that a further low-flow-speed absolute instability can exist when structural damping is incorporated.

All of the theoretical analyses described immediately above considered flexible panels of infinite extent. In doing so, the importance of convective instability is understated because it ultimately 'washes out' of a localised spatial region in the long-time limit. For a finite panel different wave-dynamics and instability evolutions occur. Our numerical experiments, [9], that incorporated fixed panel leading and trailing edges uncovered a further convective instability and showed that the destabilisation of a finite panel is dominated not by absolute instability, but by a combination of upstream- and downstream-propagating convective instabilities at flow speeds below the absolute-instability threshold. This paper considers a more general class of flexible-wall structure and demonstrates that that hydroelastic destabilsation by convective instabilities prevails for finite systems.

2. Computational Methods and Investigation

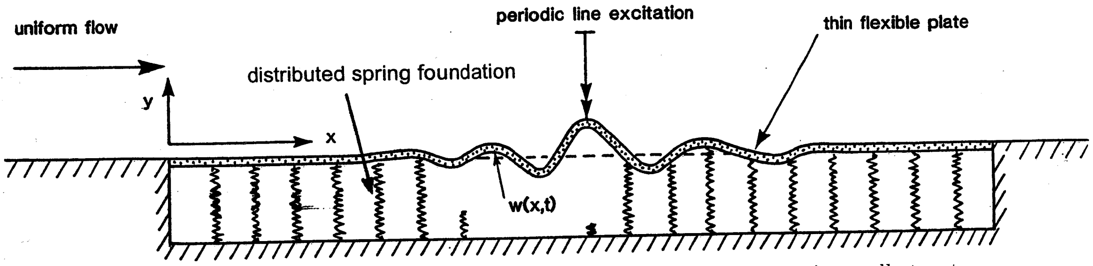

Figure 1. Schematic of the flow-structure system for a plate-spring wall structure.

Figure 1 is a schematic of the general system that we study. The key difference from previous theoretical studies with a source of excitation is the inclusion of the spring foundation. This leads to a system with two control parameters, the non-dimensional flow speed, U, as for the unsupported plate, and the non-dimensional spring-stiffness coefficient, K. In contrast to the unsupported plate, a dispersion-relation analysis predicts distinct non-zero divergence-onset and modal-coalescence flutter critical flow speeds; these were respectively derived in [10] as $U_D = (2)(3^{-\frac{3}{8}})K^{\frac{3}{8}}$ and $U_F \approx \sqrt{2}K^{\frac{1}{4}}(K^{\frac{1}{4}}+1)^{\frac{1}{2}}$. Our investigation concerns the instability regime $U > U_D$. We also note, see [11], that the structure of the dispersion relation for a plate-spring wall is identical to that of a thin elastic shell with K replaced by the shell's radius of curvature. Thus, the destabilsaton mechanism identified in §3 below will, most probably, apply to fluid-loaded finite elastic shells with fixed ends.

Our computational methods for the fully coupled system combine a boundary-element method to solve the Laplace equation subject to the wall-generated interfacial kinematic boundary condition with a finite-difference method to solve for the wall motion driven by the fluid pressure and the applied line-excitation. In contrast to a theoretical boundary-value approach, there is no prescription of wall deformation, nor is the frequency of interfacial waves restricted to that of the line-excitation.

We also model a flexible wall comprising a homogeneous viscoelastic continuum; for this wall the two control parameters are the the non-dimensional flow speed and wall thickness. The wall dynamics are modelled using a specially developed finite-element method capable of accommodating a near incompressibility of a rubber-type material. Again, our investigation focuses upon the destabilisation of the wall at flow speeds above that of divergence-onset for this type of wall.

3. Illustrative results and brief discussion

Figure 2a shows a typical result for a spring-backed flexible plate for a flow speed $U_D < U < U_F$ with oscillatory line-excitation applied at its mid-point. The salient feature to note is the ultimate emergence of a pair of distinct unstable waves from the leading and trailing edges. Both have downstream-directed phase velocity but their wall energy-density propagations are in opposite directions. The higher wavenumber wave seen near the trailing edge propagates upstream whilst the lower wavenumber wave propagates downstream. Subsequently, each time that a wave reaches the spatial extent of its propagation, permitted by the finite length of the panel, it launches its counterpart. Thus wholescale instability of the panel occurs through this combination of convective instabilities. We also note that this panel-destabilsation mechanism also occurs in the flow-speed regime $U > U_F$, whereas a dispersion-relation analysis predicts modal-coalescence flutter. Figure 2b shows a typical result for a viscoelastic continuum. The initial excitation was a point impulse applied the panel's mid-point. Like the result of Fig. 2a, it is found that wall instability is ultimately dominated by the pair of convective instabilities seen to emerge from the leading and trailing edges of the panel. In both Figs. 2a and 2b the wave types that ultimately dominate can also be seen emanating from the initial source of excitation at earlier times; thereafter the panel ends effectively serve as wave-excitation sources.

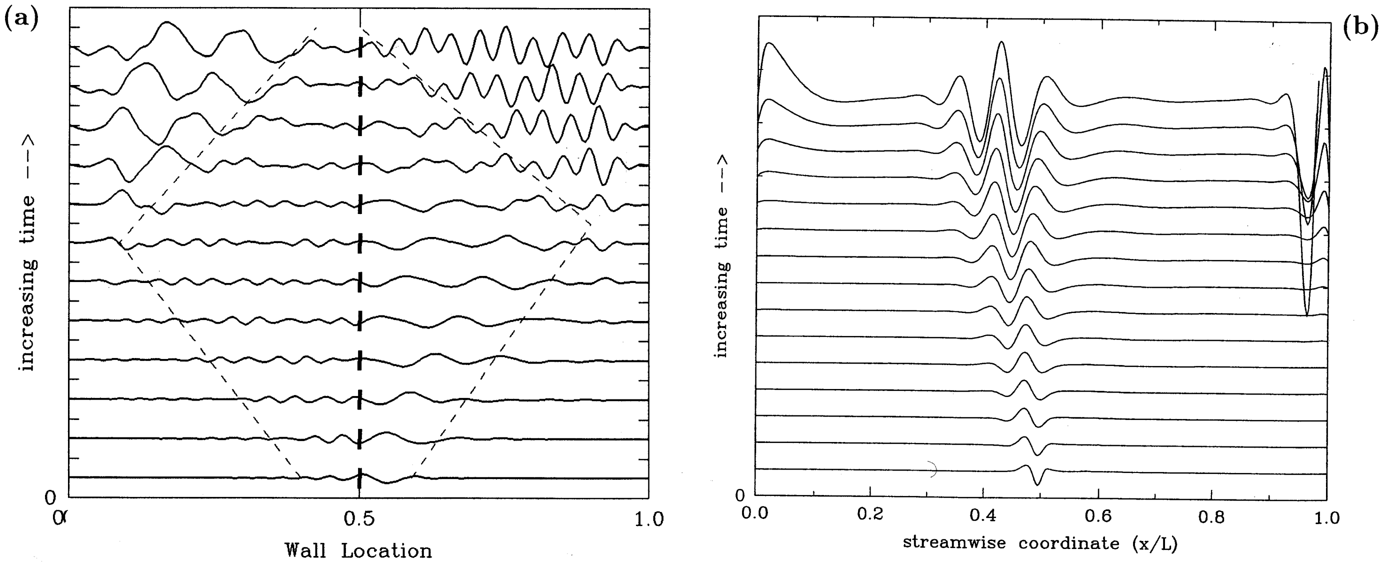

Figure 2. Space-time plots of wall-surface deformation showing the destabilsaton of: (a) a spring-backed flexible plate with oscillatory excitation at its mid point and, (b) a viscoelastic continuum initially excited by a point impulse. (The fluid flow is from left to right.)

In summary, we demonstrate that convectively unstable waves are of crucial importance in the ultimate hydroelastic destabilisation of finite flexible panels. Moreover, the characteristics of these waves are independent of the applied excitation, instead, being governed solely by the flow-structure properties. From the results of our numerical experiments, we are able to devise a frequency-wavenumber chart that offers an improved description of system instability than predictions based upon the dispersion relation for the corresponding infinite system.

References

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