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Dynamics of a partially confined, discharging, cantilever pipe with reverse external flow

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ABSTRACT

The potential for fluid-elastic instability of hanging cantilevered pipes subjected to simultaneous internal and external axial flows is investigated. Such systems may lose stability by amplified oscillations (flutter) or buckling (static divergence). The system of interest is a flexible tubular cantilever hanging concentrically within a rigid outer tube of larger diameter. Flow inside the cantilever is directed from the clamped end to the free end. Upon exiting the cantilever, the fluid flows in the opposite direction in the annular region between the outer tube and the cantilever. The rigid outer tube is of variable length and it can cover part of the length of the cantilever. This system has applications in brine production and salt-cavern hydrocarbon storage. A linear model is derived based on the work of Paidoussis, Luu and Prabhakar; the presence of the shorter outer rigid tube is taken into account in a simplified way. Series solutions are obtained using a Galerkin method with Euler–Bernoulli beam eigenfunctions as comparison functions. Experimental results are presented and compared with the theoretical model. Additional computations are performed to quantify the effect of confinement (i.e. the narrowness of the annular region) on the cantilever stability, as well as the effect of confined-flow length, for both the short laboratory-sized system and long brine-string-like systems. An increase in these parameters gives rise to flutter for short systems, or a succession of flutter and divergence for long systems. In addition, the effect of the system length is investigated. Increasing length results in asymptotic behaviour, with both the critical flow-velocity and associated frequency reaching limiting values. Sufficiently long systems lose stability by divergence rather than flutter.

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1. Introduction

This investigation is concerned with flow-induced vibrations of a flexible tubular cantilever, hanging concentrically within a shorter rigid outer tube, thus forming an annular channel between the two, as shown in Fig. 1. The whole system is immersed in incompressible fluid and is contained within an otherwise closed cavity, with the exception of one inlet into the cantilever, and one outlet to the annular space between the cantilever and the rigid tube. Fluid is directed as internal flow from the clamped towards the free end of the cantilever and exits as a free jet in stagnant fluid. Because of conservation of mass, initially stagnant fluid is then forced through the annular region, as a bounded reverse external flow, over only the upper portion of the cantilever.

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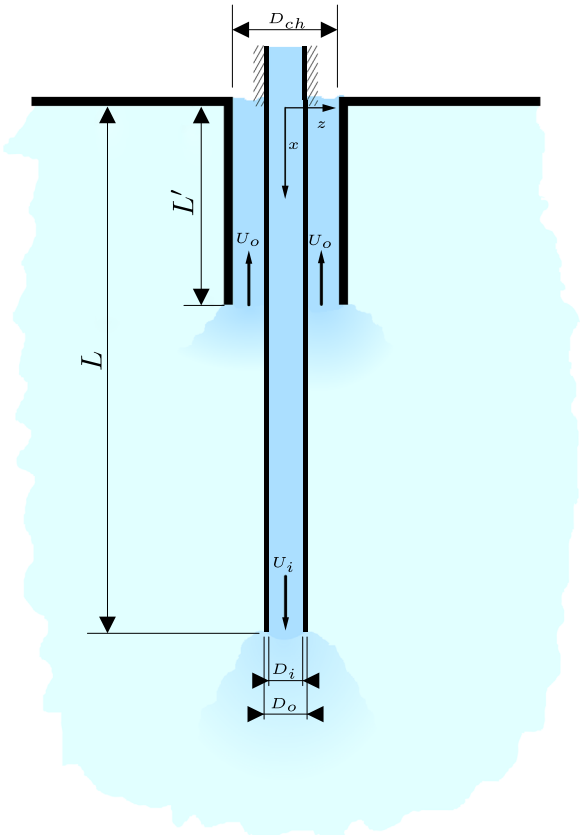

Fig. 1. Schematic of the problem at hand. A hanging flexible cantilever discharges fluid which is in turn aspirated through a shorter annulus.

This piping arrangement has applications in brine production and in the salt-cavern hydrocarbon storage industry. In fact, flow-induced vibrations of the piping is a known problem in salt-cavern operations (Ratigan, 2008). The research described in this paper was motivated from a desire to potentially improve the design of hanging tubular cantilevers so as to avoid problems with flow-induced vibration.

Work on tubular beams subjected to both internal and external flows has been done by a few researchers over a period of many years. Most of the work done involves concurrent, i.e. in the same direction, internal and external axial flows. Cesari and Curioni (1971) consider theoretically the static stability of horizontal tubular beams subjected to concurrent internal and external flows, for various end conditions. A few years later, Hannoyer and Paidoussis (1978) consider both clamped–clamped tubular beams as well as cantilevers fitted with a tapered end-piece, with a more systematic approach, and with concurrent but independent internal and external flows. They provide both theoretical and experimental results in support of their model. Subsequently, Païdoussis and Besançon (1981) consider clusters of tubular beams subjected to internal and concurrently to bounded external axial flow. Finally, Paidoussis et al. (2008) consider only theoretically the dynamics of long hanging tubular cantilevers conveying fluid downwards which, after exiting, is directed upwards as counter-current external flow. This is an idealization of a drill-string system used in oil and gas exploration and production, with the internal and external flows related by conservation of mass.

The evolution of system behaviour with increasing length is of interest, since practical applications involve cantilevered pipes of the order of 1 kilometre in length. Studies on long hanging pipes with only internal flow (Doaré and de Langre, 2002), as well as long hanging ribbons (Lemaitre et al., 2005) and horizontal cantilevered cylinders subjected to external axial flow (de Langre et al., 2007), have shown both theoretically and experimentally that both the critical flow-velocity for instability, as well as the frequency of the instability, tend asymptotically towards limiting values as the length of the system is increased.

Fig. 1 shows the geometry and defines the key dimensions of the system. The x-axis lies along the undeflected centreline of the cantilevered pipe, while the z-axis lies in the lateral direction. The length of the cantilever is denoted by L, while L' is the length of the outer tube and consequently of the annular passage. The area-averaged flow velocity inside the cantilever is denoted by U_i, and U_o is the area-averaged velocity in the annulus (naturally this is external flow with respect to the cantilever).

The organization of the paper is as follows: Firstly, in Section 2 the derivation of the theoretical model as well as the method of solution are discussed. Secondly, in Section 3 a set of experiments involving small, rubber, tubular cantilevers is detailed and a comparison is made between the experimental and theoretical results. Next, in Section 4 the theoretical model is further explored by generating solutions for the small rubber cantilevers for a range of geometric parameters much

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