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The onset of flow-rate limitation and flow-induced oscillations in collapsible tubes☆

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Abstract

Experiments were mounted to investigate the onset in a 'Starling resistor' of collapsible-tube oscillation, at the lowest possible Reynolds number so as to facilitate matched numerical simulations. The protocol adopted was to set pressure outside the tube and inside the tube at the upstream end, constant and equal to each other, then to progressively lower the downstream pressure past the point of tube collapse and, when this occurred, of oscillation onset. The working fluid was a glycerine/water mixture, and the silicone-rubber tube was suspended horizontally in air. Measurements were made of pressures and flow-rates and of the cross-sectional area at the approximate location of maximum oscillation; separately, the cross-sectional area of the tube in relation to transmural pressure was measured. Parameters varied in the flow experiments were the length of rigid pipe downstream of the collapsing tube, and the fluid viscosity. The pressure/flow-rate coordinates of both the point of peak flow-rate achieved before flow-rate limitation, and the point of oscillation onset, were satisfactorily independent of the pipe length downstream. Both points occurred at flow-rates that decreased with increasing fluid viscosity, so that the corresponding Reynolds numbers decreased more so. Oscillation did not break out below a Reynolds number of about 290 unless there was external mechanical agitation of the apparatus. The amplitude of oscillation decreased progressively towards zero at this point as viscosity was raised. After the flow-rate peak, flow limitation causes a local flow-rate minimum. When oscillation occurred, it started just before this minimum, and died away at the minimum.

Keywords: Instability; Self-excited oscillation; Rubber tube; Wave speed; Choking; Flow regulation

1. Introduction

The deceptively simple system consisting of a flexible segment in an otherwise rigid pipe, acted upon by sufficient external pressure to cause collapse while a flow courses through, has exercised the minds of researchers for well over half a century. Motivation is provided on the one hand by the resemblance of such tubes to many of the conduits in the human body, and on the other by the extent to which the system thus described is canonical, permitting different laboratories to work both experimentally and by computer simulation on comparable versions differing only in readily

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measurable parameters. The behaviour is complex enough to remain unpredictable today thanks to the strong two-way fluid-structure interaction between the flow and its tubular boundary, and in particular includes the ability to regulate flow-rate and the ready propensity to self-excited oscillation.

The question of what drives an observed flow-induced oscillation of a collapsed tube is subtle, in that it can be posed at many different levels. At simplified levels it can be argued that we understand what is going on already. The most simplified level is that of lumped-parameter models (Conrad, 1969; Bertram and Pedley, 1982). While each allows a plausible explanation of what might cause oscillation, they are collectively unsatisfactory in that they cannot describe features of the mechanics which are clearly likely to be important, such as wave travel. Many of these deficiencies can be resolved by going to a one-dimensional model (explicit variable dependency on time and streamwise position). These allow description of many more types of potential oscillatory instability (Cancelli and Pedley, 1985; Hayashi et al., 1998; Brook et al., 1999), but ultimately fall short, because the 1-D formulation of highly 3-D phenomena (the tube geometry and the flow within) requires assumptions that collectively limit the extent to which the model can be compared with experiment. In the end, one still has no confidence that the model describes the mechanism of oscillation at play in the closest corresponding experiment. 2-D models (Pedley, 1992; Luo and Pedley, 2000) can avoid these unreal assumptions, but posit an experiment that is impractical: a 2-D collapsible channel. Thus ultimately one is forced to the position that nothing short of a full numerical simulation in three dimensions will do [so far achieved only for steady flow—Hazel and Heil (2003), Marzo et al. (2005)]. However, none of the existing experimental data-sets provides data that are both sufficiently well characterized to validate a 3-D model and in a parameter range that is amenable to today's numerical methods and computers. We therefore perceived a need for fresh experiments that address these requirements.

2. Methods

If the experiment is to be capable of numerical simulation, oscillation must occur at the lowest possible Reynolds number (Re). However, small tube dimensions reduce the extent to which the experiment can be characterised by measurement tools. We therefore chose to increase fluid viscosity instead, working with a 70:30 glycerine:water mixture and a silicone-rubber tube of inside diameter 12 mm, wall thickness 1 mm and unsupported length 228 mm. Further detail of the tube mounting is given by Bertram and Elliott (2003). The chosen mixture proportions and experimental protocol allowed us to investigate tube collapse occurring both with and without oscillation, and ensured that any oscillation was minimal; the operating-point regions where the tube is oscillatorily unstable (Bertram and Elliott, 2003) were barely entered before increasing collapse restored stability.

The protocol that we sought to follow provides the most explicit possible demonstration of the flow-rate limitation property of a collapsible tube. A constant pressure is maintained at the upstream end of the tube and the same air pressure is held constant outside. The downstream pressure is initially also the same, then is ramped down slowly, causing the flow-rate to increase from zero. Eventually the tube collapses, at which time the flow-rate peaks, and oscillations break out if conditions allow. The rate of downstream pressure reduction is ideally slow enough that the operating point essentially traverses through a continuous series of quasi-steady conditions. If this is achieved, and obviously any finite rate of descent can at best only approximate this situation, then behaviour at each point during the descent will depend only on the current values of the controlling pressures, and not on their recent history or their rate of change. Although the control-space diagrams we have previously published for this tubing (Bertram and Elliott, 2003) are not really applicable here, owing to the completely different fluid viscosity, conceptually the protocol amounts to traversing vertical lines up the diagram at horizontal locations that either barely pass through the lower left-hand corner of the basically triangular region encompassing all periodic oscillatory modes, or just skirt the region altogether.

To permit this manoeuvre we rebuilt our existing apparatus for the recirculation of liquid through a collapsible tube (Bertram, 1986). What existed previously provided for the atmospheric-pressure collection of liquid downstream of the tube, and its supply upstream at a well-regulated constant pressure, via a system that required 25 l of liquid to fill (Bertram et al., 2001). The new system (see Fig. 1) collected outflow in another, independently pressurised vessel, from which air could be slowly bled to atmosphere via a needle valve after isolation from the pneumatic supply. This provided an approximately exponential decrease of pressure, approximate because the levels in the various vessels were not wholly independent of the changing flow-rate through the tube.

To minimize aeration of the glycerine:water mixture, flow exited into the cylindrical downstream vessel via a pipe that extended below the free surface. Consequently the downstream pressure that was controlled (p_d) was not the same as the pressure at the collapsible-tube exit (p_2). Similarly the constant upstream pressure (p_u) was distinct from the pressure at the collapsible-tube inlet (p_1). The liquid pressures p_1 and p_2 were measured using Druck PDCR-200 transducers inserted into the rigid piping about 35 mm from the upstream and downstream ends of the unsupported flexible tube segment. We also measured the air pressure outside the tube (p_e), using an Endevco 8510C-50 transducer. In order to