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Experimental characterization of the oscillatory behavior of a quasi-two-dimensional collapsible channel

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ABSTRACT

Experiments are performed for a rigid, high-aspect-ratio, rectangular channel with a portion of one wall replaced by a flexible membrane (a “2D” Starling resistor). The fluid is air, which is driven by a pressure drop up to 300 Pa, producing Reynolds numbers up to 22,000. The experiments include pressure measurements at 6 locations along the channel, 1 velocity measurement, and high speed video of the membrane which is analyzed to extract the membrane motion.

The primary variables considered are membrane tension, inlet pressure, and area of the side-wall gap. Steady and unsteady behaviors are observed for the 3 membrane tensions considered. The unsteady behaviors are categorized as “traveling”, “mode 2”, or “complex” oscillations, which may be recognized by the spectral characteristics of their pressure signal. Hysteresis is clearly observed depending on how the inlet pressure is adjusted. The side-wall gap, which permits air leakage around the membrane, is an important factor, and is characterized as a function of membrane tension and inlet pressure.

1. Introduction

Deformable tubes transporting a fluid are essential to the function of the human body (blood flow, or airflow through the human airway) and other biological systems, yet are often poorly understood (Bertram, 2008; Heil and Hazel, 2011). To gain a richer understanding of the fluid–structure interaction (FSI) in such systems, simplified models may be used. An essential example of this is the Starling resistor, in which flow is driven through a flexible tube that is connected to a rigid tube upstream and downstream. A 2D analog of the Starling resistor is flow through a channel, in which a portion of one of the walls is deformable with rigid portions upstream and downstream (see Fig. 1 for an example). The 2D Starling resistor model, first studied by Pedley (1992), is particularly well-suited for those performing analytical/numerical studies; however, we are not aware of experimental results to which the simulations may be compared. Therefore, we perform experiments of a “2D” collapsible channel, with the intent of providing a validation case for FSI simulation models.

The Starling Resistor has proved to be a fruitful experimental model for illustrating many intricate behaviors within a relatively small parameter space (Bertram and Tscherry, 2006; Bertram and Elliott, 2003). While the Starling Resistor lends itself to experimentation, it provides a significant challenge for simulations given the complex 3D buckling behavior of the

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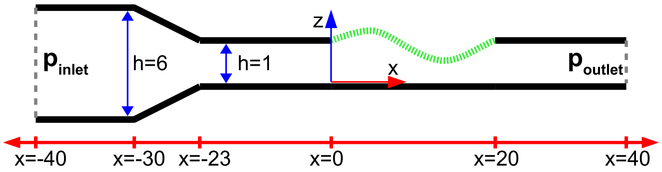

Fig. 1. Schematic of the geometry (not drawn to scale). The flexible membrane is shown with a dashed green line. The y-dimension goes into the page. All dimensions are given in centimeters. (For interpretation of the reference to color in this figure caption, the reader is referred to the web version of this paper.)

tube, the near-closure of the fluid passage, and potential self-collisions of the deformable tube (see Heil and Hazel (2011) for a discussion of analytical and numerical results for the 3D Starling resistor). However, describing the tube shape with a "tube law" (Whittaker et al., 2010) coupled with lumped parameter or 1D fluid models provides a simplified approach for simulating the Starling resistor (Shapiro, 1977; Bertram and Pedley, 1982; Cancelli and Pedley, 1985; Jensen, 1990, 1992).

The 1D fluid model may provide useful estimates of bulk flow, but it cannot resolve all flow features, and may rely on ad-hoc assumptions for estimating viscous losses (Cancelli and Pedley, 1985), which have been demonstrated to be incorrect (Luo and Pedley, 1998). The collapsible channel provides an intermediate level of complexity for computational methods between the demanding 3D description and the highly-simplified 1D model, and has been intently researched with a variety of membrane and fluid models (Luo and Pedley, 1998; Jensen and Heil, 2003; Liu et al., 2009, 2012; Pihler-Puzovic and Pedley, 2013; Xu and Jensen, 2015). Experiments cannot replicate the theoretically 2D scenario of these collapsible channel simulations; however, experiments on a collapsible channel that is largely uniform in the transverse direction may provide a useful comparison. Matsuzaki et al. (1998) performed collapsible channel experiments in which the membrane was oscillating yet controlled. Ikeda et al. (1998) performed experiments in which the membrane was unconstrained, but did not consider that they successfully overcame the challenges of achieving 2D membrane motion and controlling the leakage around the membrane edges (Bertram et al., 2003).

In this study, we have performed experiments with unconstrained membrane motion in which the side-wall gap area is a controlled parameter, which affects air leakage around the membrane. In contrast with most of the collapsible channel studies that consider a light (or massless) membrane and heavy fluid, we use a heavy membrane and a light fluid in our experiments, reflecting our intended application of airflow in the human upper airway. This causes gravity to have a pronounced effect in our experiments, as opposed to previous models where the effects of gravitation are often neglected (Xu and Jensen, 2015). We do not present simulations here, but refer the interested reader to Anderson (2014), which compares simulations using a 1D fluid model with the experimental results given in this paper.

In the next section we describe our experimental methods. Then we present our results, including: descriptions of steady and unsteady behaviors, and descriptions of global behavior as membrane tension, side-wall gap, and inlet pressure are varied. A discussion of experimental error and conclusions round out the paper.

2. Methods

The experimental geometry is illustrated conceptually in Fig. 1. The entire system was 80 cm long (x-axis), 20 cm wide (y-axis), and 6 cm in depth (z-axis, aligned with gravity). We defined coordinates with $x=0$ at the upstream edge of the membrane, $y=0$ mid-width of the membrane, and $z=0$ on the channel floor at $x=0$. The inlet occurred at $x = -40$ cm, the channel converged from $-30 < x < -23$ cm, the membrane started at $x=0$, the membrane ended at $x=20$ cm, and the outlet was at $x=40$ cm. In the converging section the channel converged linearly, from a width of 20–5 cm, and from a height of 6–1 cm, yielding a channel contraction ratio of 24. The dimensions of the collapsible portion were 20 cm long, 5 cm wide, and 1 cm in depth.

The flow was driven by a pressure inlet at $x = -40$ cm, and exited to atmospheric pressure (uncontrolled) at $x=40$ cm. The pressure above the membrane was also atmospheric pressure. This is a notable difference from most Starling resistor models, which allow the external pressure to be controlled and independent from the outlet pressure.

Photos of our experimental apparatus are shown in Fig. 2. The rigid channel was constructed from 1/2 in (12.7 mm) polycarbonate according to the dimensions described above. However, the assembled experiment had deviations from the ideal channel height ($h_0 = 1$ cm) due to imperfections in the design and machining processes. The measured dimensions are $h=1.05$ cm $(105\% h_0)$ at $x = -23$ cm, $h=1.100$ cm $(110\% h_0)$ at $x = -2$ cm, $h=1.225$ cm $(122.5\% h_0)$ at $x=22$ cm, and $h=1.225$ cm $(122.5\% h_0)$ at $x=40$ cm; these values are valid across the channel width $(-2.5 \le y \le 2.5$ cm).

The membrane material was an "ultra soft polyurethane" (durometer 40 OO, 1/8 in thick) from McMaster-Carr; we measured the thickness to be 2.92 mm and the density to be 1239.8 kg/m^3. The Young's modulus was estimated to be $E=93{,}000$ Pa, as shown in Appendix A. The unsupported membrane span was 20 cm, but some membranes were cut with shorter unsupported lengths to observe the effects of tension. Tension 1 had a 20 cm unsupported length and thus was untensioned; Tension 2 had a 19.5 cm unsupported length and thus was stretched 0.5 cm; Tension 3 had 19.0 cm of unsupported length and thus was stretched 1.0 cm. The membrane mounting is shown schematically in Fig. 2c. All membranes had 2 cm on either end of their unsupported section, which was attached to the underside of a removable L-shaped block