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Self-Exciting Oscillations of Elastic Tube Conveying Fluid at Laminar and Turbulent Flow Regimes

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Abstract. Behavior of elastic tubes conveying fluids has been extensively studied during last 50 years in the context of biological and physiological applications. A lot of experimental works are conducted in a large range of Reynolds numbers, and mostly at turbulent flow regimes. But it is known that biofluids often circulate at laminar regimes. The unit based on the "Starling resistor" is commonly used to study experimentally the stability of the tube with fluid flowing into it. The behavior of the tube as the part of such unit has become a separate issue, and is also widely studied experimentally, analytically and numerically. In this work we experimentally investigate the influence of the flow regime on the stability boundary and limit cycle oscillations of latex thin-walled tube. It is obtained that there are two main differences. At first, the oscillation frequency more essentially depends on a pressure drop in the tube for a fixed flow rate at laminar, than at turbulent regimes. Secondly, the oscillation amplitude is larger for the turbulent regimes, than for the laminar, when the other parameters are the same.

1. Introduction

An extensive review of advances in experimental, analytical and computational investigations of the flow into an elastic tube and the stability of such system is given in [1]. In numerous experiments researches observe such phenomena as pressure drop/flow rate relations, wave propagation and generation of instabilities. Various theoretical models are proposed to define the behavior of the elastic tube conveying fluid [2 – 4]; [3] outlines several models that have been developed to describe standard experiments in Starling resistor. There are a lot of numerical simulations of the behavior of the elastic tubes conveying fluids [2, 3, 5 – 7].

In [8, 9] detailed description of the behavior of thick-walled silicone rubber tubes conveying aqueous fluid is given. Pressure drop/flow rate curves for steady flow and equilibrium characteristics of the collapsed tube are obtained, various types of oscillations of the collapsible tube are exemplified, and little detail of the wave-forms of pressure, flow rate and area are revealed. It is shown, that the frequency of self-excited oscillations is not strongly dependent on the tube length, and the effect of the tube length is to predispose the system to a particular mode of oscillation. The investigations of the flow through thin-walled axisymmetric tubes are presented in [2]. Cross-sectional area from transmural pressure and pressure drop/flow rate relations, obtained in experiments, are used to verify the proposed lumped parameter system model. The validity of the model is confirmed by the comparison of experimental and simulation results.

Although biofluid flows are generally laminar [7], most experimental studies span a wide range of the Reynolds numbers (from hundred to several thousand) and mostly deal with turbulent flows. In [10] it is shown that for thick-walled tubes oscillations are not possible at laminar regimes. In [5] the laminar flows of various viscosities through thin-walled tubes are investigated to facilitate numerical simulations of the flow in the "Starling resistor". Results of the experiments show that the flow rate and Reynolds number at the oscillation onset do not strongly depend on downstream rigid pipe length, the oscillation frequency depends on this parameter significantly; the oscillation amplitude decreases as fluid viscosity increases.

In this paper we find the stability boundaries of the tube when the fluid flows at laminar and turbulent regimes, analyze the effect of the flow regime (laminar vs turbulent) on the limit cycle properties, the flow rate limitation and the influence of the fluid viscosity on the tube behavior.

2. Experimental Unit and Conditions

An experimental apparatus for the recirculation of liquid through the elastic tube is shown in Figure 1. Working fluids are water and glycerin mixtures of various concentrations. The working fluid flows in a closed loop and is isolated from the ambient air to protect the glycerin mixture from aeration. The fluid is carried to the base tank by the pump and enters to the elastic tube from there. Latex Penrose tubes of 8mm diameter are attached at each end to the rigid tubes of the same diameters. Elastic tubes with a length-to-diameter ratio from 50:1 to 35:1 are used. The results presented do not depend on the elastic tube length.

An external pressure p_e in the chamber is constant. The flow through the elastic tube occurs under the pressure drop $\Delta p = p_1 - p_2$. p_1 and p_2 are upstream and downstream pressures. The pressure drop in the tube is changed by the flow rate Q or downstream pressure p_2. The flow rate Q is controlled by an adjustable resistance and is measured by the flowmeter. p_2 is controlled by the position of a draining hose. Absolute and differential pressure sensors and microphone are used to measure the frequency and the amplitude of the elastic tube oscillations.

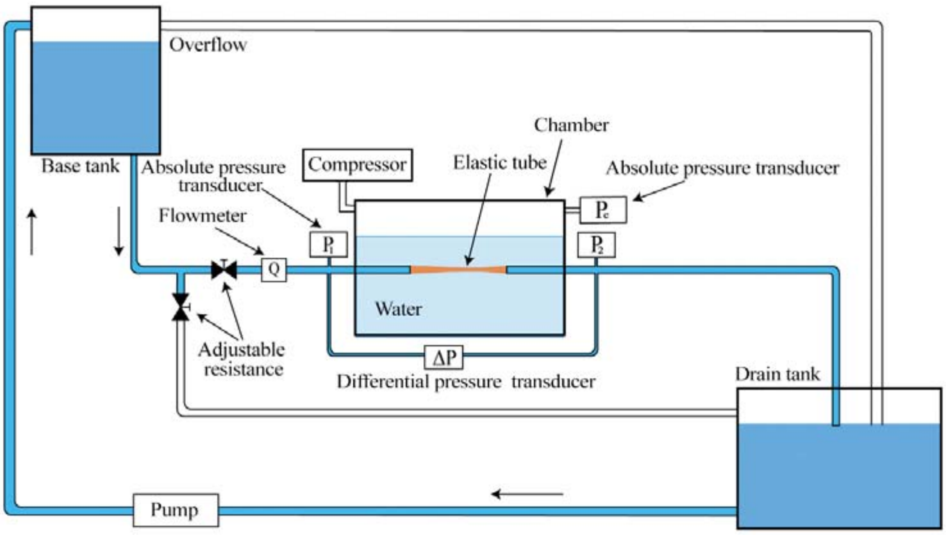

Figure 1. Apparatus for investigations of self-exciting oscillations of elastic tubes conveying fluid.

At first, we conduct the experiments at turbulent flow regimes in the flow rate range Q = 1.5-9 l/min with the step ~ 1 l/min. The working fluid is water in this case. For each flow rate we change the pressure drop Δp in the tube, find the stability boundary and the pressure drop Δp_s, which corresponds to the last cylindrical form of the tube before it begins to collapse. After it, for each fixed flow rate and corresponding Δp_s, we use the formula for the resistance coefficient at laminar regimes in the tube $\lambda = 64/Re$, and calculate an appropriate viscosity (and concentration) of the glycerin mixture, which provides for each flow rate the same pressure drop in the tube at laminar regime. So we can compare the tube behavior at turbulent and laminar regimes, when the other factors (the geometry, the flow rate and the pressure drop) are equal. This is particularly significant, when we compare the stability boundaries at laminar and turbulent regimes.

3. Results of Experiments

At first, we study the influence of the fluid viscosity on the stability boundary (in terms of Q and p_2) and limit cycle for both turbulent and laminar regimes. Reynolds number based on the Penrose tube diameter are varied in the range $3000<Re<18000$ for turbulent, and $400<Re<2000$ for laminar regime. The experiments reveal that the stability boundary and the character of limit cycle oscillations do not significantly depend on the fluid viscosity for both turbulent and laminar regimes. When the stability is lost while keeping $p_1 - p_e$ constant and increasing Δp, the tube first oscillates in the following manner (Figure 2): two collapses followed by a delay in the stable state, then again two collapses, etc. For higher Δp, the tube collapses three times followed by a delay; then four, five, and up to nine times; for higher Δp single-frequency oscillations are finally established and lock the tube. The limit cycle of this type occurs for laminar and turbulent regimes, but the dependence on Δp is more pronounced at turbulent regimes. For laminar regimes single-frequency oscillations lock the tube a little quicker. Stability boundaries are closely adjacent for laminar and turbulent regimes and fluid viscosity does not affect them (Figure 3).

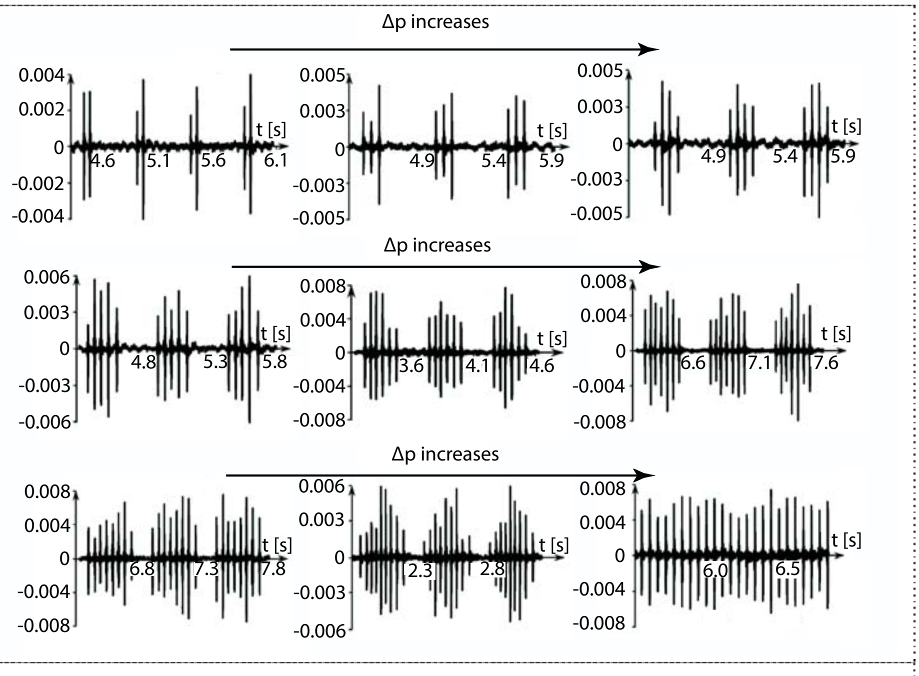

Figure 2. Various types of oscillations (corresponding to various numbers of consecutive tube collapses followed by a delay). Microphone readings. Turbulent regime.

It is significant, that after the tube loses the stability an acquainted phenomena, called "flow rate limitation", is observed for both laminar and turbulent flow regimes. It is that the flow rate does not change, when the pressure drop increases.

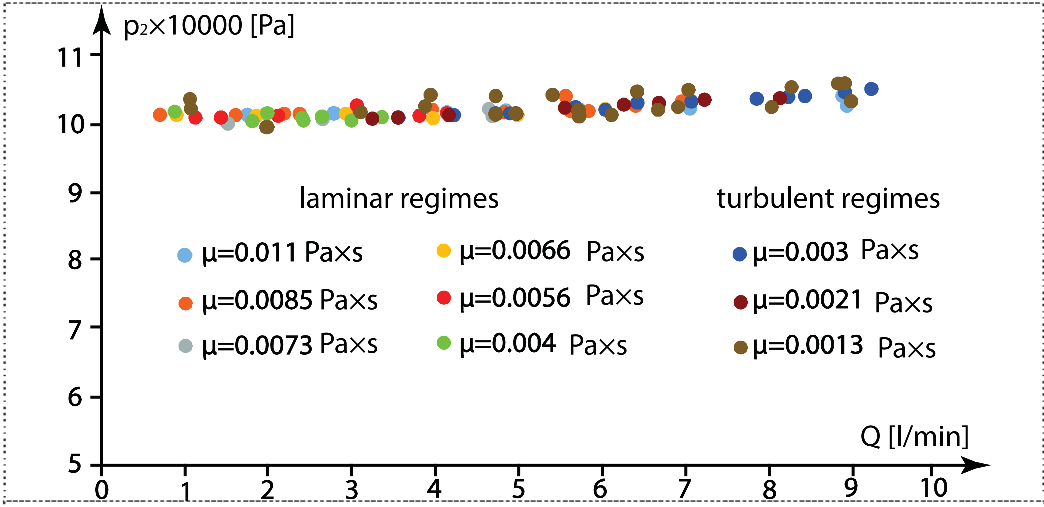

Figure 3. Stability boundaries. Dependence on fluid viscosity and flow regime.

The first difference between turbulent and laminar regime is that the oscillation frequency after the establishing of single-frequency oscillation is more significantly affected by the pressure drop at laminar regimes. In Figure 4 the deepest color corresponds to the highest frequency, white to the stability. So we see that the color changes faster for fixed Q with Δp increase at laminar, than at turbulent regimes.

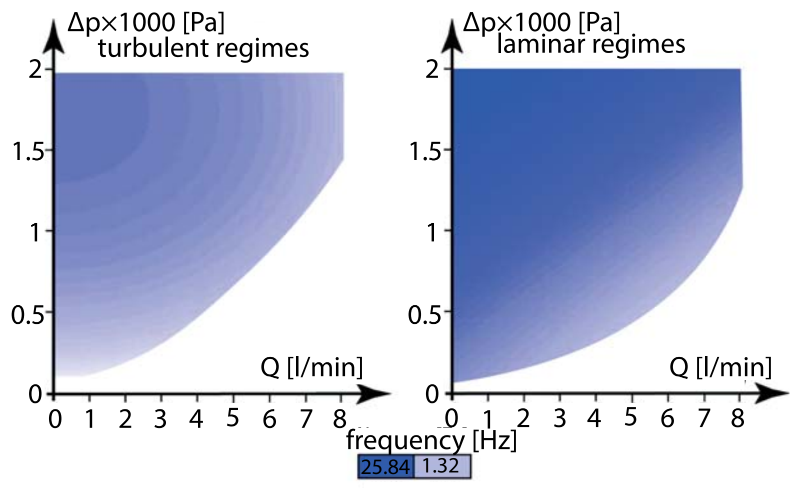

Figure 4. The oscillation frequency vs the flow rate and pressure drop relations for turbulent and laminar regimes.

The second difference is that the oscillation amplitude at laminar regimes is essentially lower than at turbulent, so that sometimes the oscillations do not fully block the tube at laminar regimes (Figure 5).

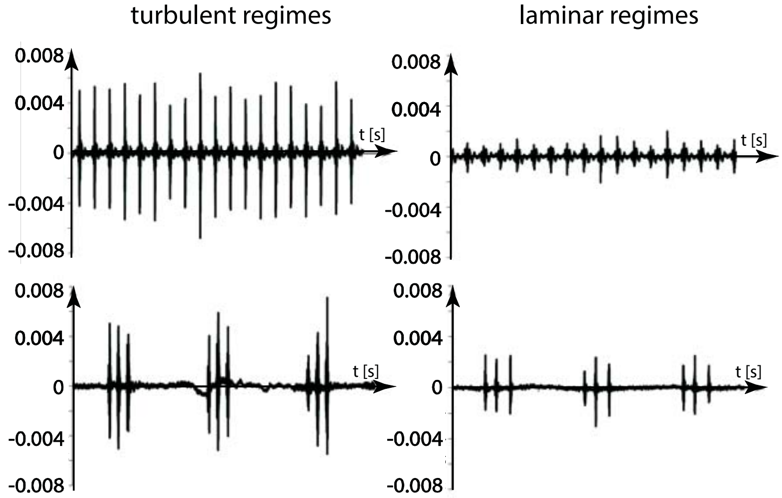

Figure 5. Oscillation amplitudes. Dependence on the flow regime.

References

[1] James B Gr and Oliver E J 2004 *Annu. Rev. Fluid Mech.* **36** 121-47
[2] Katz A I, Chen Yu and Moreno A H 1969 *Biophysical Journal* **9** 1261-79
[3] Pedley T J and Luo X Y 1998 *Theoret. Comput. Fluid Dynamics* **10** 277-94
[4] Jensen O E 1990 *J. Fluid Mech.* **220** 623-59
[5] Bertram C D and Tscherry J 2006 *J. of Fluids and Structures* **22** 1029-45
[6] Heil M and Hazel A 2011 *Annu. Rev. Fluid Mech.* **43** 141-62
[7] Hazel A and Heil M 2003 *J. Fluid Mech.* **486** 79-103
[8] Bertram C D 1986 *J. Biomechanics* **19** 61-9
[9] Bertram C D, Raymond C J and Pedley T J 1990 *J. of Fluids and Structures* **4** 125-53
[10] Bertram C D and Elliot N S J 2001 *Proceedings of the ASME Summer Bioengineering Conference 27 June – 1 July, Snowbird* **50** 383-4