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Analyzing the Effects of Key Design Factors of a Negative-Differential-Resistance (NDR) Microfluidic Oscillator–an Equivalent-Circuit-Model Approach

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Abstract. Numerical study on dynamic hydroelastic problems is usually rather complex due to the coupling of fluid and solid mechanics. Here, we demonstrate that the performance of a hydroelastic microfluidic oscillator can be analyzed using a simple equivalent circuit model. Previous studies reveal that its transition from the steady state to the oscillation state follows the negative-differential-resistance (NDR) mechanism. The performance is mainly determined by a bias fluidic resistor, and a pressure-variant resistor which further relates to the bending stiffness of the elastic diaphragm and the depth of the oscillation chamber. In this work, a numerical study is conducted to examine the effects of key design factors on the device robustness, the applicable fluid viscosity, the flow rate, and the transition pressure. The underlying physics is interpreted, providing a new perspective on hydroelastic oscillation problems. Relevant findings also provide design guidelines of the NDR fluidic oscillator.

AMS subject classifications: 76-10

Key words: Microfluidic oscillator, hydroelastics, equivalent circuit model, negative differential resistance.

1 Introduction

Microfluidic manipulation is an important topic in the studies of the fast developing micro total analysis system (μ-TAS) and microreactor technologies [1,2]. Due to the inherent low-Reynolds number (Re) flow characteristics at micro-scales, special techniques

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are required in the design of microfluidic functional components such as micropump, micromixer, microvalve, etc. [3]. These design methods are commonly categorized into active ones which use external actuators (e.g., using pneumatic, electric, magnetic, acoustic, optical, centrifugal forces) [4–6], and passive ones by dint of specially designed channels [7–9]. Actuators provide better control flexibility, but external electric devices inevitably increase the system complexity. In comparison, passive methods are more reliable but usually require complex channel structures. Therefore, both have their advantages and limits.

Some atypical microfluidic designs incorporate deformable elastic materials. These devices operate in the passive way, i.e., at constant inlet conditions, they can provide sophisticated flow controls [10–13]. Without resorting to external resources, their operation attributes to the dynamic response of the elastic structures or fluid-structure interaction (FSI) effects. In our previous studies, we reported a hydroelastic microfluidic oscillator which, at a constant driving pressure, produces self-excited oscillation converting a steady laminar flow to oscillatory flow [14, 15]. This device has exhibited great potential in applications such as droplets active control [16], microfiltration enhancement [17], fluid mixing and chemical process intensification [18–21].

The microfluidic oscillator functions through FSI-induced oscillations of an elastic diaphragm, and it is essentially a dynamic hydroelastic problem. Such FSI phenomena are usually rather complex. In traditional studies on macroscopic fluid systems, relevant numerical analysis requires the coupling of CFD (computational fluid dynamic) and mechanical models, and it remains a challenging task today [22–24]. In comparison, for microfluidic devices, their analogy to electric circuits can be utilized to facilitate the design and performance analysis. For above-mentioned hydroelastic microfluidic oscillator, an equivalent circuit model was established, which reveals that it works the way as an electric negative-differential-resistance (NDR) oscillator [25]. A variety of the oscillation behaviors can be interpreted accordingly. The equivalent circuit model of the NDR oscillator provides a facile and alternative method to analyze its characteristics. Especially, it allows direct examination on the effects of the design parameters, and hence greatly reducing the enormous computational resource normally required using CFD methods. This is of significance for device optimization.

In this study, the design space of the NDR microfluidic oscillator is explored numerically using the equivalent circuit model. Relevant analysis and findings provide a new perspective to understand the hydroelastic oscillations in microfluidic systems. It also presents useful design guidelines about how to control its working characteristics to meet specific application requirements, e.g., to process highly viscous fluids, to increase the throughput, etc.

2 Key design factors and main characteristics of the NDR oscillator