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Dynamic characterization of a polymer-based microfluidic device for distributed-load detection

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ABSTRACT

This paper presents an experimental study of the dynamic characteristics of a polymer-based microfluidic device for distributed-load detection. The core of the device is a rectangular polymer microstructure embedded with an electrolyte-filled microchannel. Exerted by a rigid cylinder probe, distributed loads deflect the microstructure and consequently alter the geometry of electrolyte in the microchannel, yielding recordable resistance changes. Using a customized experimental setup, the sinusoidal response of the device is measured with the overall sinusoidal load as the input and the sinusoidal deflection of the device as the output. The recorded data are processed to obtain the amplitude ratio, F_0/z_0, of the load to the device deflection and the phase shift, ϕ, between the two signals. These two variables are then utilized to fit the dynamic stiffness and damping of the device for extracting its system-level parameters. Three devices of different designs are fabricated and tested, and best-fit values for the system-level parameters of these devices are extracted. Through comparing the measured results among these devices, non-intuitive insight is shed on how key device design parameters and the probe used affect the dynamic characteristics of the device.

1. Introduction

In recent years, polymer-based microfluidic devices have been explored for single-load [1–4] and distributed-load detection [5–9]. Generally speaking, these devices consist of a compliant polymer microstructure and an embedded electrolyte-filled microchannel or microchamber for transduction. Owing to its incompressibility, electrolyte underneath a microstructure needs to flow in/out of a microchannel or a microchamber during operation. Therefore, these polymer-based microfluidic devices are heavily damped mechanical systems, as compared with those under-damped silicon-based physical sensors (e.g., accelerometers, tuning-fork gyroscopes, and mass sensors) [10–13]. A network analyzer is commonly employed to measure the frequency response of a silicon-based sensor, where a resonant peak is readily identified and gives rise to its resonant frequency and mechanical Quality factor (Q) [10–13]. In contrast, a heavily damped load sensor fails to exhibit a noticeable resonant peak in its frequency response and thus its resonant frequency and Q are unattainable through the instrument, as evidenced by a recent study on measuring the frequency response of a load sensor, which contains a cantilever embedded in a silicone elastomer [14]. Yet, since these polymer-based microfluidic devices function as physical sensors, their dynamic characteristics, including natural frequency and damping ratio, play a critical role in determining their ultimate performance, including response time, load resolution, as well as the maximum detectable frequency of sinusoidal loads [15].

Bearing similar configurations as these microfluidic devices for load detection, micropumps, which incorporate a compliant polymer microstructure above or underneath liquid in a microchamber, have been extensively studied for its dynamic performance [16–22], due to its relevance for determining the maximum amount of transported liquid. In a micropump, liquid in a microchamber flows from an inlet to an outlet. In contrast, electrolyte in a microfluidic device for load detection flows in and out of a microchannel or a microchamber from its two ends simultaneously. Therefore, the experimental technique for measuring the dynamic characteristics of a micropump cannot be adopted for microfluidic devices for load detection.

The majority of the studies on microfluidic devices for load detection have focused on experimentally demonstrating their feasibility of detecting dynamic loads [1–9]. However, very little work has been conducted on their dynamic characteristics [4,5,7]. This might be largely due to the fact that the heavily damped nature of these devices makes it extremely difficult to identify a resonant peak in their frequency response. Although a preliminary analysis

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on the frequency response of this type of devices was conducted, no experimental study has been followed to validate the analysis [1]. Moreover, this analysis does not take into account the interaction between the structure and electrolyte embedded in the structure, as well as the effect of the inlet/outlet for electrolyte.

To address this challenge, this paper presents an experimental study of the dynamic characteristics of a polymer-based microfluidic device for distributed-load detection. Using a custom experimental setup, the frequency response of the device is measured with the sinusoidal load as the input and the sinusoidal deflection of the device as the output. Since a resonant peak of the device is not expected to be readily noticeable and non-intuitive complex interactions among different components of the device may manifest in the frequency response, the measured frequency response is processed into the dynamic stiffness and damping as function of frequency, in order to obtain its natural frequency and damping ratio. As compared with our previous work on this device [5,6] and the related work in the literature [1–4,7–9], the original contributions of this work include: (1) an experimental method is established for measuring the dynamic characteristics of a microfluidic device for load detection; and (2) the complex interactions among different components of the device are identified regarding their effect on the dynamic behavior of the device. It must be pointed out that although the basic concept used in this work, namely, processing the frequency response into the dynamic stiffness and damping as a function of frequency, as will be seen in Sec. 3, has been well established, it has not been utilized to examine a microfluidic device for load detection. To the best knowledge of the authors, this work is believed to be the first of its kind on studying the dynamic characteristics of a microfluidic device for load detection using this concept.

The rest of the paper is organized as follows. The design and operation of the polymer-based microfluidic device is presented in Section 2. The theory underlying the experimental method for measuring the dynamic characteristics of the device is described in Section 3. The experimental method and associated data analysis are detailed in Section 4. In Section 5, the measured results on three devices of different designs are processed to obtain the dynamic characteristics of the devices; and the significant insight is shed on how the dynamic characteristics of the device vary with some device design parameters and the probe used. At the end, the concluding remarks are given in Section 6.

2. Device design and operation

Fig. 1 shows the schematics of a polymer-based microfluidic device for distributed-load detection [5,6], together with its key design parameters. The device consists of a rectangular polymer microstructure embedded with an electrolyte-filled microchannel and five electrode pairs distributed along the microchannel length. Together with the electrode pairs, one body of electrolyte in the microchannel functions as five distributed resistive transducers. During the device operation, a rigid cylinder probe is utilized to exert distributed loads on the microstructure. Consequently, the portion of the microstructure above the microchannel deflects and alters the geometry of electrolyte in the microchannel. Thus, the deflection of the microstructure registers as resistance changes at the locations of the distributed transducers [23]. Two reservoirs at the ends of the microchannel are utilized to inject electrolyte into the microchannel and provide a conduit for electrolyte in the microchannel to flow in/out. Two plugs are inserted into the reservoirs of the device for preventing electrolyte from spillover. The device is fabricated using a standard polydimethylsiloxane (PDMS) based fabrication process [4]. Fig. 2 shows the fabricated devices of three different designs. Note that the microstructure is much wider than the microchannel ($W_M \gg w_E$), and the deflection of the microstructure occurs largely in its portion above the microchannel. In this work, the deflection of a device is defined as the deflection at the top surface of the microstructure, which is in contact with a cylinder probe used in the experimental measurement. Thus, the probe displacement is equivalent to the deflection of a device, as will be seen later on. Table 1 summarizes the key design parameters of the three devices, the sizes of the probes used, as well as their static stiffness measured from their static performance characterization [6], as shown in Fig. 3. Owing to the viscoelastic nature of PDMS, these devices exhibit a little hysteresis [24] and experience structural damping. However, as compared with viscous damping caused by the electrolyte in a device, the damping from the PDMS microstructure is completely negligible and thus is believed to have no effect on the dynamic behavior of a device.

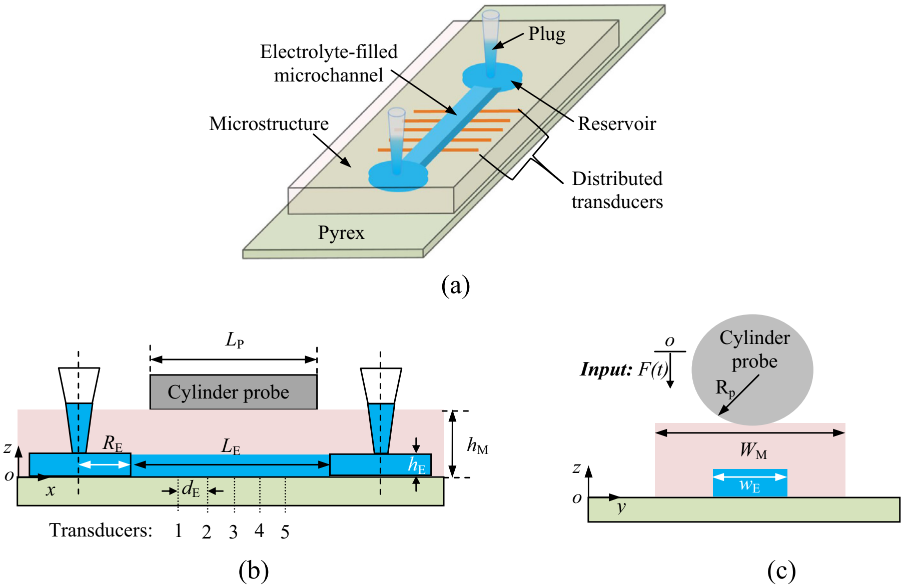

Fig. 1. Schematics of a polymer-based microfluidic device for distributed-load detection (a) 3D view (b) side-view along the device length and (c) side view along the device width (out of proportion for clear illustration).