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A scalable, minimal contact device for the characterization of elastomer membrane deformation

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Abstract

We have developed a simple microfluidic device that allows us to model the peak deflection experienced by an elastomer membrane when under a dynamic pneumatic or hydraulic actuation. The device uses fluidic displacement principles to accurately display the volume change experienced by an expanding membrane. This volume change is then used to calculate the peak deflection height of the membrane. The device has been fabricated using already well established dry film techniques commonly used in the field of microfluidics. Its simple design does not require any complex or expensive electronics and experimental results show the device’s ability to record deflections over a range of membrane diameters down to a resolution of 38 μm. Simple geometry changes can allow nanoscale resolution measurements. The device represents a low cost method of membrane deflection characterization at the micro and nanoscales.

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1. Introduction

Membrane based sensors and actuators are fundamental in many applications in micro-engineering from pressure sensors to micro-pumps and valves, lab-on-a-chip systems and as actuators in robotic gripping devices [1-4]. When it comes to these applications, being able to accurately measure, calibrate and control the membrane deformation characteristics plays a key role in operational efficiency and the accuracy and control of the overall system. There are several different current approaches for measuring membrane deflection characteristics. These include techniques such as interferometry and atomic force microscopy [5-6]. Measuring the changes in voltage and
capacitance over electro-active or conductively coated polymer membranes can also determine characteristics in relation to membrane deformation [7]. These current technologies however, have limitations when it comes to either speed, the complexity or the cost of the systems and equipment. New and novel methods to address such issues are being researched in order to better understand the membrane deflection model [8]. We report on a novel, simple, low cost device to show how the peak deflection of a circular membrane under pressure can be determined accurately using basic fluid volume displacement principles. The design of the device presented is such that no complex or expensive electronics or sensors are needed when using the device. The sensitivity of the device can be easily scaled up or down as required by simply altering the geometric dimensions of the device’s micro-channel.

2. Methodology

The device itself utilizes Archimedes’s principle where the mass of fluid displaced by an object is equal to the mass of the object [9]. As mass is related to volume via density, the device uses the displaced volume of a fluid to determine the volume change within an expanding circular membrane. Under uniform pressure, the deflection shape of a clamped circular membrane is almost spherical [10]. Assuming uniform thickness throughout the membrane, the peak deflection (h) of the membrane can be calculated by the formula for a spherical cap (1), where \( V \) is the volume under the membrane and \( r \) is the radius.

\[
V = \frac{\pi h^2}{3} (3r - h)
\]

The device consists of two wells connected by a microfluidic channel. One well is sealed using a flexible membrane of the same material to that of which is being measured. This stops fluid running freely through the device while also allowing the actuating membrane to expand with minimal resistance. The dimensions of the channel determine the length of travel made by the displaced fluid. By changing the dimensions, it is possible to increase or decrease the sensitivity and resolution of our measurement. The other well is filled with fluid and a circular membrane is clamped over the well using an O-ring to form a tight seal. As pressure is applied to the membrane, it expands and fluid in the well is displaced, causing it to travel a specific distance along the channel. This principle is demonstrated in the cross sectional figures, see Fig. 1 and Fig. 2.

2. Fabrication

To fabricate the device, traditional microfluidic fabrication techniques are employed [11], using a photo resistive film to pattern a substrate material. Ordyl 940 photo resistive film (40μm thick) is applied to a prepared stainless steel substrate layer. A micro-lithography photo mask defines the staggered square wave pattern of the channel, which in this case is 200μm wide. The square wave pattern increases the overall length of the channel while also providing an easy measurement scale for recording the fluid progression, see Fig 3. The assembly undergoes a series of UV exposure and developer wash steps before the newly exposed channel is sealed with another layer of photo resistive film attached to a layer of polymethyl-methacrylate (PMMA) substrate via acrylic transfer adhesive, see Fig.4.
The device reported here has channel dimensions of 40μm x 200μm. As each individual line segment of the square wave pattern measures 1.5x10³μm, this equates to a volume of 0.012mm³ per segment. Channel definition plays a key role in the accuracy of the device and so the channel is examined using a scanning electron microscope (SEM), see Fig. 5 and Fig. 6.

4. Testing & Results

Theoretical calibration curves are calculated to show the peak membrane deflection change in relation to the volume change within the membrane. Using the volume for a spherical cap formula mentioned previously (1) and membrane diameter sizes of 10, 6, 5 and 2.5mm, the resultant curves are shown below, see Fig.7. As we know the volume of the channel in the device, we can calculate the sensitivity of the device for these diameters. The sensitivity reaches 37μm for each channel segment for the 10mm diameter membrane.
For the experiment, circular membranes are clamped over the open well of the calibration device which is filled with dye solution. Subjecting the membranes to a series of predetermined pressures from a compressed air feed causes the membrane to expand and displace fluid from the well. Fluid travel lengths are recorded from the device each time the membrane is actuated and the mean value is calculated. This is repeated for each pressure value and for each different diameter of membrane. The length of the fluid travel is converted into its equivalent volume. Peak deflection is calculated by rearranging equation (1) and solving the cubic equation for \( h \). The results of the experiment are graphed above, see Fig. 8. As actuation pressure increases, the volume of expansion in the membrane also increases as does the fluid travel along the device. The order of the curves from the experimental results demonstrate that, while the resultant fluid travel is less the smaller the membrane diameter, greater pressures are needed in order for the smaller diameter membranes to achieve the same peak deflections as the larger diameters.

5. Conclusion

The device allows us to predict the peak deflection of the membrane in relation to actuation pressure. It acts as expected when the smaller diameter membrane is introduced, where the range of peak deflection height decreases, due to the increased resistance against membrane deformation, but the rate of change of deflection increases, due to the smaller volume of membrane. Future work will incorporate nanoscale measurements, with thinner photo resistive films readily available and the ability to reduce the channel width and length of each segment. Sensitivity can be increased still if fluid progression along the channel is monitored under microscope. The device has already been successfully deployed as a calibration tool for a dynamically actuated probe.

References