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Precision density and viscosity measurement using two cantilevers with different widths

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ABSTRACT

We introduce a novel method for fast measurement of liquid viscosity and density using two cantilevers with different geometries. Our method can be used for real-time monitoring in lab on chip systems and offer high accuracy for a large range of densities and viscosities. The measurement principle is based on tracking the oscillation frequencies of two cantilevers with a phase-locked loop (PLL) and comparing with reference measurements with a known fluid. A set of equations and a simple algorithm is developed to relate the density and the viscosity to the frequency shifts of the cantilevers. We found that the effect of the density and the viscosity can be well separated if cantilevers have different widths. In the experiments, two Nickel microcantilevers (widths 25 μm and 100 μm, length: 200 μm, thickness: 1.75 μm) were fully immersed in the liquid and the temperature was controlled. The actuation was using an external electro-coil and the oscillations were monitored using laser Doppler vibrometer. Thus, electrical connections to the cantilevers are not required, enabling measurements also in conductive liquids. The PLL is used to set the phase difference to 90° between the actuator and the sensor. Calibration measurements were performed using glycerol and ethylene glycol solutions with known densities and viscosities. The measurement error with the new method was lower than 3% in density in the range 995–1150 kg/m^3 and 4.6% in viscosity in the range 0.935–4 mPa.s. Based on the signal-to-noise ratio, the minimum detectable difference in the viscosity is 1 μPa.s and the density is 0.18 kg/m^3. Further improvements in the range and the accuracy are possible using 3 or more cantilevers with different geometries.

1. Introduction

The ability to monitor viscosity and density with low sample volumes is important for various industrial applications and medical applications. Industrial producers of oil and ink use viscosity and density measurements for quality control purposes. In health care, blood viscosity is monitored for early diagnosis of diseases. MEMS based sensors may provide versatile tools meeting the requirements of the large range of applications. Microcantilevers are widely used for viscosity and density sensing applications due to their simple microfabrication [1–10] as well as being well suited for applications where measurements from small volumes are required. The dynamic behaviour of a cantilever depends on the viscosity and the density of the liquid medium it operates in [1]. Hence, by tracking the resonant frequency and the damping (Quality factor), significant data about the density and viscosity can be gathered. The effects of density and viscosity on both resonant frequency and quality factor are coupled to each other[1–3]. Some groups worked on analytical methods to separately obtain the viscosity and density values from experimental data [3–5]. Although the derived equations are applicable for a large viscosity range, they require precise vibration amplitude measurements, to obtain high accuracy. A general approach to separate viscosity and density effects experimentally is to relate quality factor changes with viscosity and resonant peak shifts with density [6–9]. This approach is also used with other types of MEMS structures like Suspended microchannel resonators (SMR) [11,12] and piezoelectric MEMS resonators [13–16] and suspended microcapillary resonators [17]. With this approach in order to attain high sensitivity in a broad dynamic range, frequency sweeps with high frequency resolution

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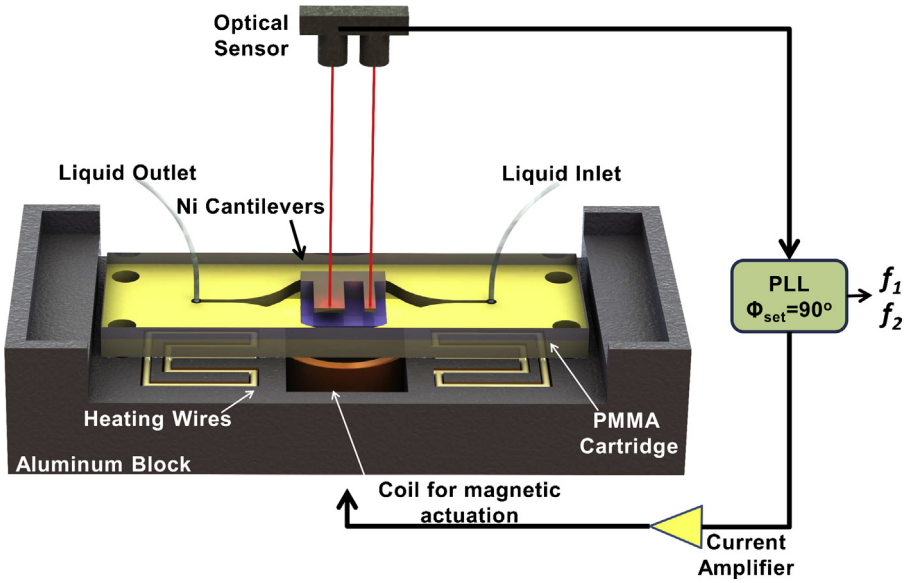

Fig. 1. The schematic representation of the measurement principle. actuation and sensing is conducted with an external electro-coil and laser doppler vibrometer (LDV), respectively. two cantilevers are immersed in the liquid and have different widths (25 μm and 100 μm) and the same thickness (1.75 μm) and length (200 μm).

is necessary. This is generally a slow process and network analysers should be employed to speed up the process [8]. To the best of our knowledge, in the published literature measuring both the frequency and the quality factor is necessary to separate the effect of viscosity and density.

In our previous works we utilized nickel cantilevers to measure viscosity of blood plasma and serum [18,19]. We achieved an accuracy of 6% and a viscosity sensitivity of 0.01 mPa.s but the density measurement was not possible and it was measured with another equipment. Our magnetic actuation and optical read-out scheme enables simultaneous monitoring of different assays in parallel channels [20,21].

In this paper, we introduce a novel empirical method for simultaneous measurement of viscosity and density by using cantilevers with different widths. The resonant frequency and quality factor is dependent on the hydrodynamic force acting on the cantilever. This hydrodynamic force is a coupled function of both viscosity and density. The effect of viscosity and density will differ depending on the cantilever geometries [4,22]. We fabricated cantilever designs with varying widths while keeping the length and the thickness same. Calibration liquids with water solutions of ethylene glycol and glycerol were prepared [6,7]. We use a commercial PLL to track the frequency at constant phase, record the frequency change in these different liquids with respect to DI water. For each cantilever design the same procedure is repeated and calibration constants are determined. After the calibration step, the viscosities and densities of different solutions are determined with the proposed method and the results are compared with reference measurements.

2. Materials and methods

2.1. Measurement principle and fabrication

Fig. 1shows the schematic representation of the measurement setup. The nickel cantilevers are subjected to an AC magnetic field provided by an external electro-coil. Two permanent magnets are placed to right and left sides of the coil to generate DC magnetic field and saturate magnetization of the nickel cantilevers. (Not visible in Fig. 1) [19]. The read-out is conducted with a LDV. This optical read-out scheme can be altered with an interferometric read-out for easier packaging and multiplexing capability which was shown in our earlier studies [18,20]. The PLL module of the commercial lock-in amplifier (Zurich Instruments HF2LI) is utilized for frequency tracking. The nickel cantilevers are fabricated with a simple one-mask microfabrication process [18,23]. After the chips are fabricated they are placed inside a PMMA channel [18,21]. This channel is consisting of three different PMMA layers. The bottom layer houses the chip; channel geometry is patterned into the mid-layer by laser cutting and the top layer is used a lid. The thickness of each layer is 1 mm. A circular geometry is required to obtain a perfect liquid exchange and avoid liquid residues from the previous sample. The chips are bonded to the bottom layer by double sided tape. Finally, all of the layers are bonded to each other by using chloroform. A temperature controller with 0.1 °C precision is used [21]. The sample volume required to make measurement is 100 μl and it can be further reduced to 10 μl with optimized chip and channel design.

2.2. Theoretical background

When operating in a liquid medium a hydrodynamic force is applied to the cantilever. This hydrodynamic force per unit length, F_{hydro}, includes two separate terms [4]:

$$F_{\text{hydro}} = -g_1\dot{\omega} - g_2\ddot{\omega} \quad (1)$$

$\omega = \omega(x,t)$ is the deflection function of the beam axis. According to Sader's theory [1], the liquid mass accelerated with the cantilever vibration can be assumed as a cylinder with mass per length equal to. The and *parameters* can be expressed as [5]:

$$g_1 = M_L(2\pi f_L)\left(b_1\frac{\delta}{w} + b_2\left(\frac{\delta}{w}\right)^2\right) \quad (2)$$

Table 1
Densities and viscosities of the reference solutions for calibration experiments conducted at 23 °C.

Solution	Density (kg/m^3)	Viscosity (mPa.s)
DI H_2O	997	0.935
G8.6 (8.6% glycerol)	1021	1.175
E10 (10% ethylene glycol)	1010	1.175
G5 (5% glycerol)	1010	1.060