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Evaluation of a vibrating micromachined cantilever sensor for measuring the viscosity of complex organic liquids

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Abstract

A novel micromachined viscosity sensor is evaluated in particular for measuring complex organic liquids with non-Newtonian behavior. The sensor contains a micromachined cantilever, which is electromagnetically driven by an ac current in a permanent magnetic field utilizing the Lorentz force. The change in the resonance frequency is monitored when the oscillating cantilever is immersed in a viscous liquid. This procedure can be used to determine the viscosity of the liquid. We evaluate the sensor for a series of test liquids in a wide viscosity range from 10 to 500 mm^2/s and compare its performance to a conventional viscometer and to a microacoustic thickness shear mode (TSM) viscosity sensor. In particular, its behavior for non-Newtonian oil mixtures containing polymer-additives is considered.

Keywords: Micromachined cantilever; Viscosity sensor; Oil viscosity

1. Introduction

For a number of applications, such as, e.g., online monitoring applications, there is an increasing need for miniaturized viscosity sensors [1,2]. The use of microacoustic resonators for viscosity measurements is described in [3–5]. A well-known device is the thickness shear mode (TSM) resonator, which, for Newtonian liquids, is sensitive to the liquid's density and viscosity [6,7]. Depending on the molecular structure of the liquid, the measured viscosity varies for non-Newtonian liquids with the applied frequency and the shear amplitude [4]. Compared to conventional laboratory viscometers, TSM resonators operate at high frequencies (in the MHz range) and apply small shear movements of some tens of nanometers. For non-Newtonian fluids, the results are thus often not comparable to conventional viscosity measurement results, as obtained, e.g., with Ubbelohde-method or rotational viscometers [5]. In [5], we reported that oils containing polymer-additives yielded different viscosities in measurements with TSM resonators when compared to laboratory viscosity measurement methods.

To get closer to the rheological domain tested by laboratory viscosity measurement methods, a resonator needs to measure at lower frequencies and higher shear amplitudes [4]. The use of a piezoelectric cantilever is described in [8]. With the micromachined cantilever sensor presented in this paper, we aim at getting results, which are more comparable conventional laboratory methods, especially when measuring oils containing polymer-additives. During mechanical oscillation, this electromagnetically driven cantilever produces shear waves in viscous liquids, similar to the glass fiber described in [9,10]. Due to this interaction, the resonance frequency and the damping of the cantilever are influenced by the viscosity of the liquid, which can be utilized for viscosity sensing.

2. Fabrication and functional principle

A U-shaped cantilever is fabricated using micromachining technology, by evaporating metal lines onto backside passivated $\langle 1\,0\,0 \rangle$ Si-wafers patterned with an image reversal

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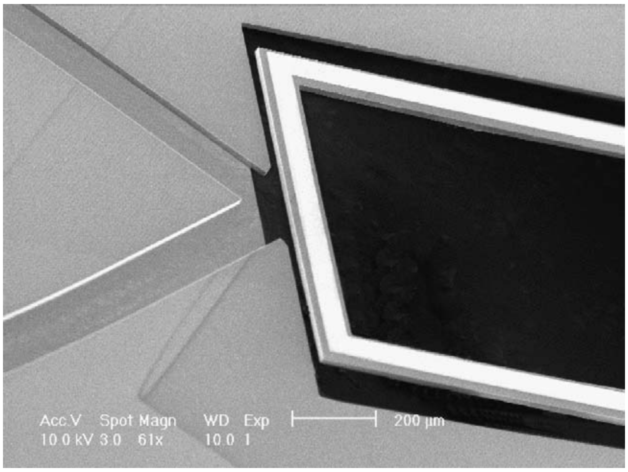

Fig. 1. SEM micrograph of the cantilever.

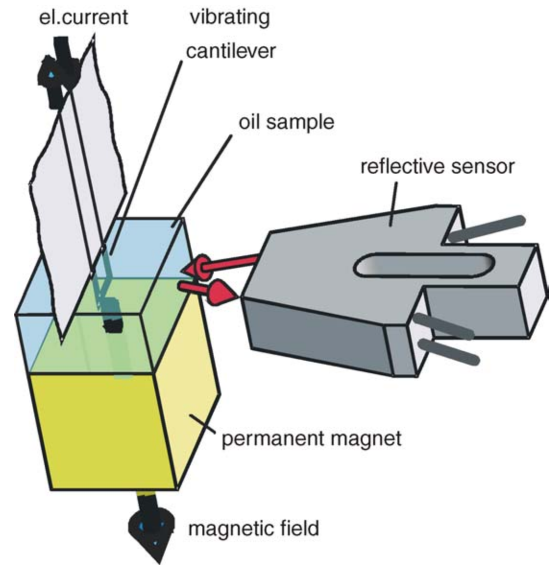

Fig. 2. Experimental setup to determine the viscosity of the oil sample with a vibrating cantilever.

photo-resist. The resulting conductor-path (lead) consists of a 0.5 μm thick and 60 μm width Au-layer. The wafer is then wet-etched anisotropically from the backside, leaving a thin Si-membrane. The shape of the cantilever is etched from the topside using a RIE-process. The finished cantilever has a length of 1500 μm and an overall width of 1100 μm. The cross-sectional dimensions are 100 by 15 μm. Fig. 1 shows a SEM micrograph of the cantilever.

In presence of a static magnetic field the cantilever bends if a current is passing through the electrically conducting path on the surface by the Lorentz force. The degree of bending can be determined by means of an optical method. The application of this device for the measurement of magnetic fields has been described in [11].

For the present application, the magnetic field is provided by a permanent magnet. By impressing an AC current through the conducting path on the cantilever, the mechanical resonance characteristics of the cantilever structure can be determined by varying the excitation frequency. If the device is surrounded by a viscous liquid, the damping and the resonance frequency will change according to the density and the viscosity of the liquid.

3. Experimental setup

The micromachined cantilever is immersed in the oil sample, which is contained in a small PMMA-container directly mounted on a permanent magnet, as shown in Fig. 2.

The cantilever is excited by the Lorentz force generated by the ac current flowing through the lead on the surface of the cantilever in the magnetic field. The order of magnitude of the resonance amplitude achieved is about 20 μm. The driving current is variable in frequency. The free resonance frequency in air is at 8 kHz.

For the experimental setup, the oscillation of the cantilever is detected by a commercially available reflective sensor placed outside the PMMA-container. Its IR-beam is reflected on the Au-lead depending on the actual deflection of the cantilever. Using a lock-in amplifier setup, the amplitude and phase relation between excitation current and cantilever displacement can be determined to obtain a frequency response describing the system. The amplitude should be treated only as a relative value, because absolute amplitude measured depends on the strength of magnetic field, the transparency of the oil for the IR-beam, and the position of the cantilever in the vessel.

4. Results

To evaluate the device performance, measurements with engine oil samples have been performed. Engine oil is a complex mixture, typically based on 80% of organic base oil supplemented with 20% of different additive components. Some of these additives modify the rheological (e.g., Newtonian) behavior of the oil, such that the measured viscosity crucially depends on the method of measurement.

First, we characterized the sensor in a wide viscosity range by using a series of sample liquids as shown in Table 1. We used diesel oil mixtures, which were prepared using several mineral base oils with different viscosities (types SN 85, 150, and 500) and a simple mixture with a high molecular weight polymer (OCP olefin-co-polymer), which is a common viscosity modifier additive. Oils with polymer-additives show non-Newtonian behavior, thus the measured viscosity is more susceptible to the method of measurement.

Fig. 3 shows the resulting frequency response from 5 Hz to 6 kHz when the cantilever is immersed in the oil samples. The measurements were performed at room temperature. Since the absolute amplitude depends on several factors, like magnetic field and transparency of oil, the amplitudes in Fig. 3