A Spiral Spring Resonator for Mass Density and Viscosity Measurements

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Abstract

Most recently introduced viscosity and mass density sensors utilize vibrating resonant mechanical structures interacting with the sample fluid where the resonance frequency and the quality factor are affected by both, the fluid’s viscosity and its mass density. Unlike singly clamped beams, straight, doubly clamped structures are advantageous when using electromagnetic excitation and read-out based on Lorentz forces which allow high excitation forces and read-out signals. However, classical straight beams such as bridges are subjected to high cross-sensitivities of their resonance frequencies to ambient temperature. To overcome high spurious temperature dependencies but to benefit from the straight doubly clamped approach, a spiral spring resonator applicable as viscosity and mass density sensor has been designed.

Keywords: Tuning fork, viscosity, mass density;

1. Introduction

Resonant viscosity and mass density sensors are very attractive devices for fluid characterization and condition monitoring in the oil, automotive and food industry. Thus, these devices have been of great interest and many principles have been reported during the past decade see, e.g., [1]. Amongst these devices, electromagnetic actuated and inductively read-out principles showed to be especially advantageous as they allow high excitation forces and read-out signals. Such devices consist of electrical conductive mechanical resonators being excited to harmonic oscillations by means of Lorentz forces on sinusoidal currents in the presence of an external magnetic field. For read-out, the motion-induced voltage on the conductor can be utilized. By sweeping the excitation currents frequency, the mechanical resonators frequency response (which is affected by the sample liquid) can be recorded. As the read-out signal shows a quadratic dependence on both, length of the effective conducting paths and the external magnetic field, the electrical conductor (i.e., the mechanical oscillator) should be preferentially straight and thus doubly clamped. However, doubly clamped structures showed a relatively large cross-sensitivity of their resonance frequency to temperature due to internal mechanical stresses. For instance, a cross-sensitivity of

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Figure 1: Sensor principle a) An electrical conductive spiral spring, immersed in a sample liquid, carries sinusoidal currents in the presence of an external magnetic field and thus oscillates laterally. By sweeping the excitation current’s frequency around the fundamental mode and measuring the motion-induced voltage on the spring, the frequency response can be recorded. In general, higher viscosities of the sample liquid yield higher damping and higher mass densities yield lower resonance frequencies. b) photograph of a first prototype, c) electrical equivalent circuit

more than 1.7 Hz/K, for a resonance frequency of about 6.8 kHz, i.e. a relative temperature coefficient of about $-246 \times 10^{-6}$ 1/K was reported in [2]. This cross-sensitivity directly decreases the sensors accuracy and thus should be preferentially small. To benefit from the advantages of a straight structure which could be easily integrated in a Halbach array [3], [4] yielding magnetic flux densities of more than 1 T but allowing a significant reduction of the cross-sensitivity to temperature, a spiral spring resonator has been devised. There, a stretched spiral spring oscillates laterally due to Lorentz forces on sinusoidal currents in the electrical conductive spring. In contrast to conventional straight, doubly clamped structures, the normal stresses within the stretched spring are hardly affected by ambient temperature changes and thus, the cross sensitivity of the resonance frequency to temperature is small. The temperature coefficient could be reduced to $-138 \times 10^{-6}$ 1/K which corresponds to an improvement of almost 80 % compared to the results obtained with stretched tungsten wires [5]. In this contribution we outline the fabrication, discuss the device design and present first experimental results illustrating the sensors performance, i.e. sensitivity to viscosity and mass density.

2. Sensor Principle

The principle of the spring viscosimeter, a photograph as well as an electrical equivalent circuit of the device are depicted in Fig. 1. A spiral spring, placed in an external magnetic field and carrying sinusoidal currents, is immersed into a sample liquid. Due to Lorentz forces on the AC currents in the spring, the latter oscillates laterally, which in turn induces a voltage on the spring. By sweeping the excitation current’s frequency, the frequency response can be recorded, e.g. by measuring the voltage on the spring with a lock-in amplifier. In general, higher viscosities yield higher damping, i.e. lower quality factors and higher mass densities yield lower resonance frequencies. The measurable voltage $V_{\text{out}}$ on the device is composed by a significant offset voltage (due to the device’s impedance) and the aforementioned motion induced voltage $V_{\text{M}}$, which is the quantity related to the liquid’s viscosity and mass density. As an alternative to the lock-in amplifier, e.g., an impedance or network analyzer could be used as well, where in case of the impedance analyzer, the motion induced voltage on the spring appears as an increase in impedance.

For a first prototype, a spiral spring was mounted and stretched on two brass screws which in turn were fixed with two brass screws which furthermore allowed for electrically contacting the spring, see Fig. 1(b). This clamping method is sufficient for principle investigation, and first estimation of side effects such as cross-sensitivity to temperature. However, when aiming at using the device as an accurate viscosity and mass density sensor, a more reliable clamping technique has to be developed as e.g., by mechanically cleaning the device, it might be detuned yielding a change of it’s resonance frequency (in air) which would require a recalibration procedure of the device. As a first attempt, to overcome this drawback, the spring was brazed on small brass cylinders. However, due to the high temperatures, the brazed spring’s elasticity significantly suffered from the brazing procedure and thus this approach was not further refined.

Figure 1(c) shows an equivalent circuit of the entire measurement setup of the spring viscosimeter. A series resistance $R_s$ is used to limit the excitation current to prevent from non-linear deflections. The lumped elements $R_{ss}$ and $L_{ss}$ represent the spring’s electric resistance and inductance respectively. These parameters can be identified by recording the frequency response without an external magnetic field (in this case $V_M = 0 \text{ V}$), and fitting $R_{ss}$ and $L_{ss}$ for the recorded frequency...
response of the complex voltage divider. A comparison of the recorded and the fitted model with \( V_g = 0.1 \text{ V}, R_s = 100 \text{ } \Omega, \) \( R_{ss} = 789.3 \text{ m}\Omega \) and \( L_{ss} = 332.74 \text{ nH} \) is shown in Fig. 2.

3. Response to Viscosity

To investigate the device’s response to viscosity, eleven Acetone-Isopropanol solutions were prepared featuring a viscosity range from 0.2 mPa·s to 2 mPa·s for mass densities of roughly 0.78 mg/cm³, see Fig. 3(c). There, the mass percentage of isopropanol in acetone is given in the left column of the table (\( m_I \) and \( m_A \) denote the mass of isopropanol and acetone, respectively). After mixing, the solutions were characterized with an Anton Paar SVM 3000 at 25 °C.

The recorded frequency responses and evaluated quality factors and resonance frequencies over viscosity are depicted in Fig. 3. Figure 3(a) shows a characteristic frequency response in air with a quality factor \( Q \) of 3028.6 and resonance frequency \( f_r \) of 643.75 Hz as well as 100 recorded frequency responses for every liquid at 25 °C. After the examination of a liquid, the sensor was cleaned and then a measurement in air was performed. Due to the provisional clamping method which was explained in Sec. 2, mechanical cleaning might have changed the resonance frequency of the device. The span of variations of the evaluated resonance frequencies in air (after every measurement in a liquid) was 0.6958 Hz, which is a justifiable stability for a very first feasibility study of the sensor’s principle but not for an accurate sensor.

Contrary to expectations, the resonance frequency in the second liquid is higher than for the first liquid see Fig. 3(b). As for the same liquids, this effect was also observed for tuning forks and an oscillating U-shaped wire [6], this effect can be explained due to the fact that the second liquid’s mass density is significantly lower than the first, see Fig. 3(c), which is a result of the circumstance that these kind of resonant sensors are sensitive to both, viscosity and mass density.
4. Response to Mass Density

To investigate the spring’s sensitivity to mass density, six solutions with a viscosity of approximately 1 mPa·s and mass densities between 0.78 mg/cm³ and 1 mg/cm³ were mixed and again characterized with a SVM 3000. The recorded frequency responses and evaluated quality factors and resonance frequencies as well as the values determined with the SVM3000 for viscosities and mass densities are shown in Fig. 4.

The fact, that the resonance frequency obtained for the third liquid slightly deviates from the expected behavior is assumed to be mainly effected by the imperfect clamping method. Although the obtained values for the quality factors show significant variations (−1.97 % to 3.22% for the third liquid) the trend, that higher mass densities also yield lower quality factors, is clearly observable.

5. Conclusion and Outlook

The purpose of using a spiral spring as resonator for viscosity and mass density sensing was to reduce thermally induced (normal) stresses in a doubly clamped structure which could be proofed in a first feasibility study where a temperature coefficient of \(-138 \cdot 10^{-6} 1/K\) was achieved. Furthermore, the response to viscosity and mass density was investigated and clear dependencies in both, the resonance frequency and quality factor could be observed. Regarding future work, a more reliable setup has to be designed, the sensitivities to viscosity and mass density as well as the device’s cross-sensitivity to temperature have to be further investigated.

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