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Viscosity Measurement Cell Utilizing Electrodynamic-Acoustic Resonator Sensors: Design Considerations and Issues

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Abstract

Miniaturized resonating viscosity sensors operating at frequencies in the low KHz-range offer portability and results comparable to existing lab viscometers. In this paper we will briefly describe a viscosity measurement cell based on a concept that we proposed earlier utilizing electrodynamic-acoustic resonator sensors with a design based on interchangeable resonator cards, which allow for ease of maintenance of the device and provides higher measurement repeatability. Experimental results obtained with the new resonator cards show the clear dependence of the resonance frequency and Q factor on viscosity. In addition, an experimental approach is taken to study the effects of magnetic field variations on the Q factor of the investigated resonators which are suspended by S-shaped (meander) beams and operating either in air or liquids.

Keywords: Viscosity measurement, electrodynamic-acoustic resonator, magnetic circuit, Q-factor improvement

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1. Introduction

Handheld viscosity sensors with electrodynamically excited vibrations promise results comparable to current lab measurement systems [1] due to the low operation frequencies compared to microacoustic sensors operating in the MHz-regime. At the utilized operating frequencies in the kHz-range, the penetration depth of the damped shear wave excited in the liquid still allows the analysis of complex liquids such as emulsions and suspensions [2],[3]. The vibrations are excited using Lorentz forces by passing an alternating current through a conductive mechanical plate resonator structure while having a magnetic field from an adjacent permanent magnet normal to the plate's surface (see Fig. 1). The plate then vibrates at the frequency of the exciting current and when this frequency coincides with a mechanical eigenfrequency of the resonator, the vibration amplitude increases greatly [4].

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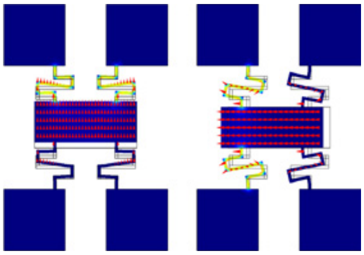
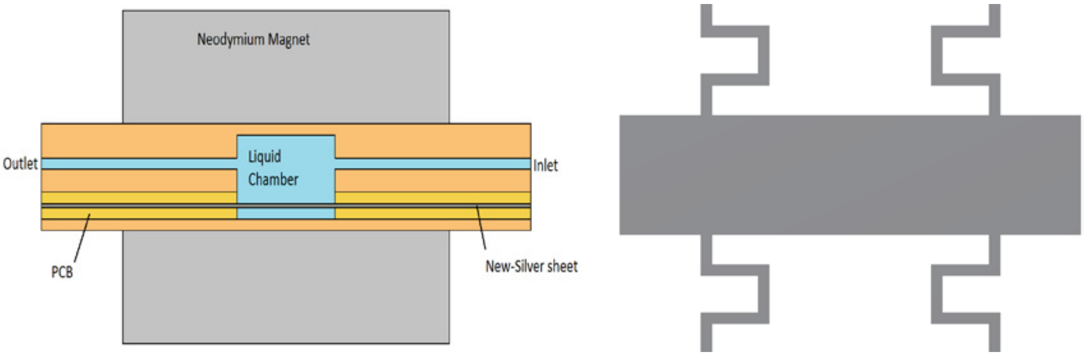


Fig. 1. Basic working principle of the sensor. The colour indicates the current density, an external magnetic field (from a permanent magnet) is oriented orthogonal to the plate yielding Lorentz forces [4].

The excitation path can be considered as the input port of the sensor. The readout is performed by utilizing the motion-induced voltage across another path of the sensor (the output port). The signal strength can be significantly improved if the ports are connected to signal transformers. The excitation methods and vibration modes as well as detection of output signals for such sensors have been described in [1],[4].

If the resonating plate is immersed in a liquid, strongly damped shear waves in the liquid are excited at the shear-vibrating surfaces. The associated entrainment of viscous liquid leads to (i) a reduction of the resonance frequency and (ii) to a damping (lower Q-factor) of the resonance characteristics. Both effects can be used to determine the viscosity of the liquid [1].

In this contribution, the focus will be on the sensitivity of the sensor to changing viscosities and the effects the magnetic circuit has on the operation of the sensor.



(a) (b)

Fig. 2. (a) Measurement cell prototype schematic (b) CAD drawing of the considered S-beam resonator plate.

2. Experimental setup

In the following we briefly describe the measurement cell and introduce the principle of the resonator card. The measurement cell, which can be seen in Fig. 2(a), consists in this specific case of two PEEK (Polyether ether ketone) structures in which the liquid holding chamber has been milled. Two closely placed magnets insure a sufficient magnetic flux density and magnetic field uniformity.

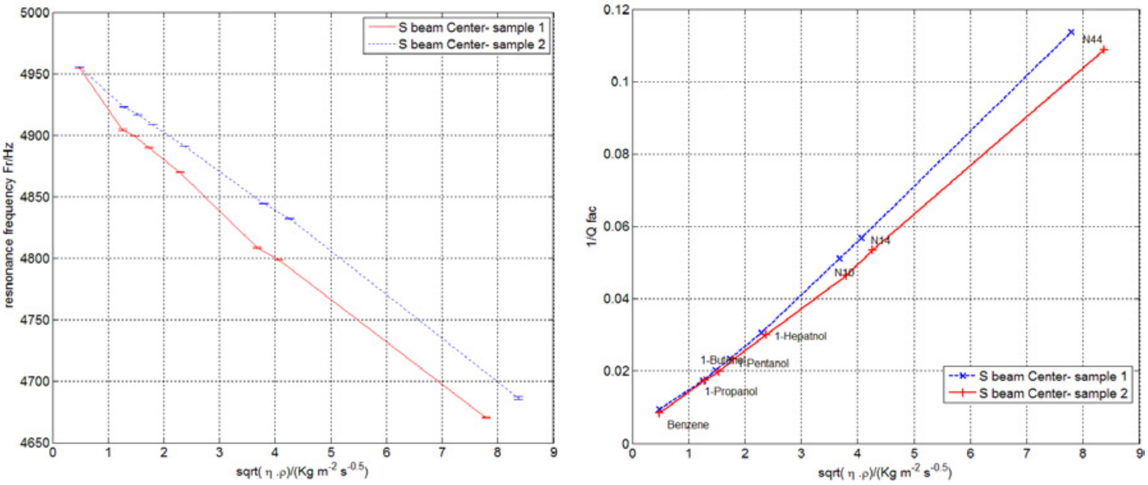
In the middle of the design lies the resonator card. This card is basically an etched mechanical resonator (Fig. 2(b)) in the middle of a sheet of New Silver (also known as nickel silver), which is a copper-nickel alloy with added zinc [5], of 150 µm thickness. The sheet metal is glued between two milled PCB or ceramic layers of various thicknesses. The card is thus represented by the sheets labeled “PCB” and “New Silver Sheet” in Fig. 2.

The used transformer circuit has been discussed in [4] and will not be revisited here. The measurements for the sensor were made using Agilent network analyzer E5061B. The excitation path of the resonator was connected to the reflection port and RF source with 0dBm nominal power at 50Ω, and the induction path was connected to the transmission port [4]. The data obtained was then processed by a curve fitting algorithm to extract the resonance frequency and the quality factor [6].

3. Experiments and results

In this contribution the focus will be on experimentally showing the sensitivity of the sensor to viscosity and on showing the effects that variants of the magnetic circuit can have on the sensors behavior.

Firstly and in order to determine the effectiveness and reliability of the design, a set of repeatability experiments were made with various resonator cards. These experiments, the results of which are depicted in Fig. 3, were carried as follow: experiments were made using viscosity standards and alcohols of known viscosities. Since the experiments were carried out at room temperature, the thermal dependence of the viscosities had to be compensated for. Reference viscosity measurements were made using an Anton-Paar SVM 3000 Stabinger viscometer.



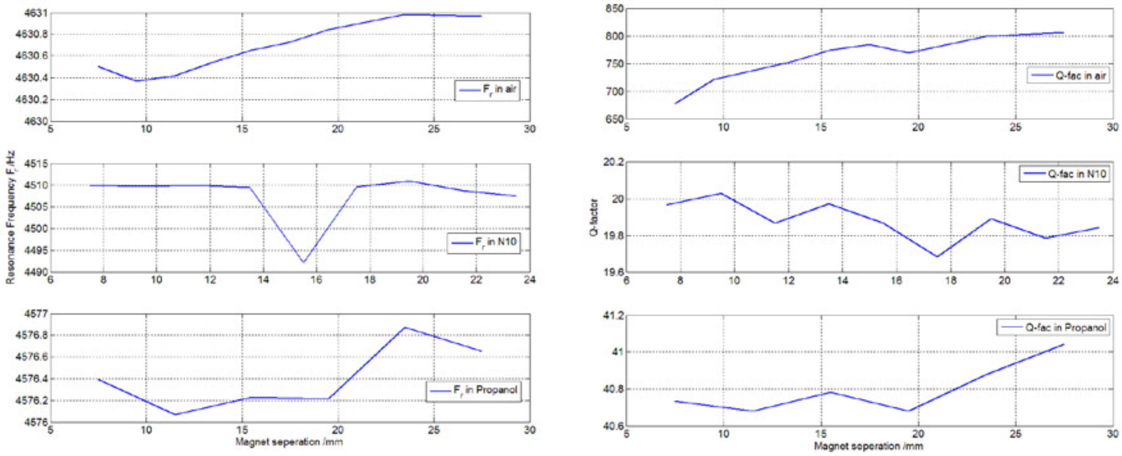
(a) (b)

Fig. 3. (a) Repeatibility tests on resonance frequency (the error bars are barely visibly at this scale), (b) Inverse Quality Factor

The graph in Fig. 3(a) shows the relation between the resonance frequency F_r and the square root of the product of viscosity η and density ρ, i.e. $\sqrt{\eta\rho}$. Fig. 3(b) shows a virtually linear relation between $\sqrt{\eta\rho}$ and the inverse of the Q-factor. In [7] it has been theoretically proven that the relation between the inverse Q factor and $\sqrt{\eta\rho}$ is an almost linear one, a behavior which is proven by our experiments.

Secondly, another set of experiments conducted was to determine the effect of varying the magnetic circuit on the resonator’s response both, in air and in liquid media. The distance separating the magnets that can be seen in Fig. 2 (a) was increased, which allows to vary both the magnetic flux density and the field's uniformity. It has been shown before [8] that the relation between the magnitude of the measured signal (induced voltage) and the magnetic field strength (hence the separation between the magnets) is a quadratic one. The main problem that arises from measurements made in weaker magnetic fields is that the lower amplitude of the received signal and thus the reduced signal to noise ratio make it very difficult to estimate the Q-factor and resonance frequency values correctly by means of standard algorithms. Therefore a suitable fitting algorithm [6] is required.

Fig. 4 below shows that the increment in magnet separation has negligible effect on the resonance frequency. And while its effects on the Q-factor in air are considerable, its effects in the two tested liquids, the viscosity standard N10 and 2-Propanol are negligible. The reason for the observed behavior is that, when the magnets are displaced away from the resonator in air, extra damping due to eddy currents is strongly reduced, thus explaining the increase in Q-factor. In liquids on the other hand, and because the contributions to the overall Q-factor add inversely, the dissipative effect due to the eddy currents is negligible. And while in theory it would be more efficient to have a higher "basic" Q-factor (i.e. the dissipative contributions when operated in air), increasing the magnets separation is not necessarily beneficial for the overall sensor performance because it strongly reduces the signal's magnitude leading to issues with the signal to noise ratio (see also above).



(a) (b)

Fig. 4. Effect of increasing magnet-separation on (a) resonance frequency (b) Q-factor, for three different media: air, viscosity standard N10 and propanol

4. Conclusion

In this contribution we introduced a miniaturized viscosity sensor operating in the low kHz frequency range making the results more comparable to existing lab viscometers (as opposed to devices operating in the MHz-range). The dependence of the resonance frequency and the Q-factor have been verified to be in accord with existing theory, and the effect of varying the magnetic flux density by means of increasing the distance between the magnets used to induce the required driving forces has been proven to be negligible or non-existing.

Acknowledgements

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