In this contribution, we present a symmetric arrangement of resonating plates for viscosity and mass density measurement. Regarding the oscillation mode, the design resembles that of micro machined tuning forks and is based on previously introduced resonating plate designs. It exhibits similar sensitivity to viscosity and mass density as the single plate resonators while having a lower damping when operated in the tuning fork mode. In this contribution we introduce the new design, present the results of FE simulations in order to determine the associated eigenmodes and examine the effects of the used actuation method on the sensor. Measurement results are presented which show the general dependence of the tuning fork design on viscosity and mass density as well as the differences exhibited by different modes, particularly the in phase and out of phase vibration modes of the plates.

Keywords: Resonating plate sensor, Symmetric plate resonators, Viscosity Density measurement.

1. Introduction

Electrodynamic-acoustic viscosity sensors operating in the low kHz range have been a topic of interest, mainly because of their extended range of applications in comparison to higher frequency operating sensors (e.g., thickness shear mode resonators operating in the MHz-range). This extended range of applications is made possible by the relatively big penetration depth of the used shear wave in comparison to that of, e.g., thickness shear mode resonators[1],[2],[3],[4].
In the following we introduce an electromagnetically actuated system of mechanically resonating plates, utilizing a design similar to that used for micromachined tuning forks [5], [6], [7]. The use of both resonating plates and tuning forks for rheological sensing applications have been previously discussed, see, e.g., [1], [2], [3], [4], [8], [9], [10]. In this work we combine both concepts to create a sensor that allows for shear-plate rheological analysis of fluids, by offering the possibility of actuating two separate shearing resonance modes with comparable magnitudes (Fig. 1(b) and (c)) without the need to apply any physical change to the measuring setup. In addition to the possibilities offered by the sensor’s two shear resonance modes, it will also allow for a setup that is less dependent on clamping conditions than the resonating plate sensor discussed in [10]. The importance of this is related to the fact that, in the process of developing a handheld viscosity measurement device, the design of the resonator has to be as independent on outside clamping conditions as much as possible to avoid any interference of these conditions with the measurements made [11].

2. Resonator design and operation principle

The new tuning fork based resonating plate design is manufactured by lithography and wet etching of Nickel-brass (new silver) as described in [3]. Fig. 1(a) shows a picture of the etched resonator glued between two milled FR4 plates. The vibrations in the mechanical resonator are excited as shown in Fig. 1(b) using Lorentz forces. By passing an alternating current through a conductive mechanical plate resonator structure while having a normal magnetic field to the plate’s surface, the plate mechanically vibrates in plane at the frequency of the excitation current. If the excitation frequency coincides with a mechanical eigenfrequency of the resonator, the vibration amplitude increases greatly. If the resonating plate is immersed in a liquid, strongly damped shear waves in the liquid are excited at the surfaces vibrating in-plane. The associated entrainment of viscous liquid leads to: (i) a reduction of the resonance frequency and (ii) to a damping (i.e. a lower Q-factor) of the resonance characteristics. Both effects can be used to determine the viscosity of the liquid [1], [2].

An FE analysis of the designed structure was conducted using Comsol Multiphysics 4.3 in order to determine the various resonance modes. The two main resonance modes of interest are the in phase and out of phase, i.e. tuning fork, shearing modes depicted in Fig. 1(b). The FE analysis also shows the Lorentz Forces acting on the plate when an input current is applied between the terminals labeled I₁ and I₂ with the shown magnetic field. The excitation path (between terminals I₁ and I₂) 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 (between terminals O₁ and O₂).
The resonator used in our experiments was actuated using a four adjacent permanent magnets configuration (Fig. 1(b)). This configuration was used because it favors the actuation of the out of phase resonance mode, while still actuating the in phase mode very efficiently. It should also be noted that both of the studied shear modes can be actuated using a two permanent magnet configuration, and a comparison of various configurations for the actuation of the sensor is the topic of future research. Fig. 1(c) shows the Bode plots of the in phase and out of phase resonance modes, with the resonator actuated using the four adjacent permanent magnets configuration.

3. Measurements in liquids

The measurements with the sensor were made using an Agilent network analyzer E5061B. The excitation path of the resonator was connected to the reflection port and the RF source (operated with 0 dBm nominal power at 50Ω), while the readout path was connected to the transmission port (operated with 0 dBm nominal power at 1MΩ). One low frequency transformer (Coilcraft Europe Ltd., UK) with winding ratios of 1:16 was used to amplify the induced voltage at the output [8].

The resonance frequency \( f_r \) and the \( Q \)-factor \( Q \) were obtained by fitting a standard second-order frequency response to the measured spectrum using nonlinear least-squares fitting methods. In [12] an accurate fitting approach is described, which is particularly suitable for systems featuring low quality factors. In particular, we applied the so-called resonance base estimation method outlined in [12] to determine \( f_r \) and \( Q \).

The fluids used for the characterization of the sensor are viscosity standards with viscosities ranging between 3.3 and 71 mPa.s and densities between 0.808 and 0.864 g/cm³. All the measurements made in liquid were made at the temperature of 25°C, maintained constant using a controlled water bath. Fig. 2(a) shows the dependence of the resonance frequency shift \( \Delta f_r \) and the damping \( D = 1/Q \) on \( \sqrt{\eta \rho} \), \( \rho \) being the mass density of the liquid and \( \eta \) its dynamic viscosity. The damping’s relation, which in our case is a linear one, as is expected from plate resonators [13], was fitted using the model described in [14]:

\[
D = \frac{1}{Q} = f_r(D_0 + D_\eta + D_\eta \rho \sqrt{f_r \eta \rho}),
\]

where \( D_0, D_\eta \) and \( D_\eta \rho \) are coefficients. The coefficients were calculated using a least squares fit and the obtained equations for both resonance modes are shown on the graph of Fig. 2(a). Fig. 2(b) shows the results of 100 consecutive measurements made with the resonator under the same conditions, at the same temperature of 25°C, and with liquids of very close viscosities in order to show the repeatability of the \( Q \)-factor measurements.

Fig. 2 (a) Plot showing the nearly linear dependence of \( f_{\text{res}} \) (here \( \Delta f_{\text{res}} = f_{\text{res,liquid}} - f_{\text{res,air}} \) where \( f_{\text{res,air}} \) is the resonance frequency in air and \( f_{\text{res,liquid}} \) is the resonance frequency in the measured liquid) and \( 1/Q \) (i.e. the damping \( D \), of the resonator’s two main resonance modes (in phase and out of phase), on the square root of the viscosity (\( \eta \)) and the density (\( \rho \)). (b) Evaluated \( Q \)-factor values of 100 measurements made in two different viscosity standard liquids illustrating the spread and repeatability of the measurement values at the constant temperature of 25°C for the two studied resonance modes.
4. Conclusion

Our work in this contribution has shown the possibility of using the introduced symmetric plate resonator for more complex rheological analysis of fluids, because of the fact that it has two different shearing resonance modes that can be easily actuated with the same setup. We have discussed the operation principle of the sensor, and shown FE simulation results depicting its various operations modes. In addition we have proven that the relation of the viscosity density to the resonance frequency and the inverse of the $Q$-factor is a linear one, and we have shown measurement results with the two different shearing modes characterized in this study.

Future work will focus on investigating different actuation methods, as well as studying the effect of various geometries on the behavior of the sensor.

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