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Characterization of LFE Acoustic Wave Liquid Sensors with Finite Element Method

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1. Introduction

Besides the well-known quartz crystal microbalance (QCM), the thickness shear mode bulk acoustic wave can also be excited in a lateral field excited (LFE) acoustic wave sensor. In the last decades, there were increasing investigations on LFE acoustic wave sensors in biochemical liquid sensing applications due to its high sensitivity, low fabrication cost, and ease of integration [1-3]. In this study, LFE acoustic wave liquid sensors are analyzed by utilizing the finite element method (FEM) incorporating with the Stokes model [4-5]. The eigen-frequency and frequency response analyses of the finite element model are implemented to provide further insight into the physical nature and mechanism of the resonance excitation. Especially, the Stokes model for isotropic viscous liquid, which has been commonly used for solving the solid-viscous liquid interaction problem, is introduced in the 3D FEM model of LFE acoustic wave liquid sensors for speeding up simulation. The sensitivities of LFE acoustic wave liquid sensors to the variations in liquid properties, including viscosity, relative permittivity, and electrical conductivity, are calculated and discussed. In the meantime, QCM sensors are also analyzed for demonstrating the benefit of the LFE sensors.

2. FEM Configuration

A 3D model of LFE acoustic wave liquid sensors was developed by using the finite element software, COMSOL. As shown in Fig. 1, the sensor substrate is an AT-cut quartz plate, whose thickness and diameter are 330 μm and 25.4 mm, respectively. The diameters and gap widths of two semi-circular electrodes placed on one surface of the quartz plate are 12.7 and 1.5 mm, respectively. The direction of the lateral electric field exciting a TSM was aligned by the direction of the gap. In this study, the gap was designed to be along the crystallographic X-axis of the quartz plate since a pure TSM can exclusively be excited piezoelectrically.

Simulation result shows that the eigen-frequency converges toward a constant of about 5.035MHz with increasing the mesh layer in thickness when the default mesh level is coarse. The mesh conditions which include the ten-layer mesh in thickness and the coarse-level mesh in cross section are a reasonable compromise between the mesh size and the computation time and hence were adopted in the following calculations.

3. Results and Discussion

3.1. Frequency-Response Analysis of pure LFE devices

In order to understand the resonance behaviors of the LFE device in detail, the frequency response is necessarily calculated. Figure 2 shows the calculated frequency response of a pure AT-cut quartz LFE sensor with the displacement field of the resonance The admittance spectrum shows only one obvious resonance peak at 5.035 MHz when the LFE sensor is excited in air. The displacement of the main resonance is an in-phase shear motion and mostly confined to the quartz disk center. This mode is identified as a pure TSM.

3.2. Sensitivity Analysis of LFE Liquid Sensors

When the bare surface of a LFE sensor is exposed to various liquid environments, the liquid can be served as a virtual electrode acting opposite to the LFE electrodes. The virtual electrode leads to a redistribution of the exciting electric field and a significant resonance frequency shift. In this section, we investigated the resonance frequency shift of the LFE liquid sensor completely covered with liquid of various properties. Note that the mesh conditions are identical in these solutions. This implies that the relative error of the frequency shift is similar to that of the resonance frequency itself; therefore, the frequency shifts caused by the variations in the liquid properties can be accurately evaluated.

The material parameters of water used in the calculation include: relative permittivity of 80, longitudinal wave velocity of 1500 m/s, density of 1000 kg/m^3, and viscosity of 1 cP. The thickness was set to 100 μm, which is reasonable for practical measurement. Moreover, this thickness was divided into 10 mesh layers to maintain a sufficient number of elements for computation accuracy.

We adopted the 3D FEM model to calculate the sensitivity of the LFE acoustic wave sensor to the variations of mechanical and electrical properties in liquid. The calculation results show

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the frequency drop is 1.1 kHz when the liquid viscosity varies from 1 to 20 cP, about 4 times as high as the QCM sensor. The results show a similar trend to the measurement in Ref [2].

The frequency shift, relative to the resonance frequency in the case of water, as a function of liquid relative permittivity is shown in Fig. 3. The LFE sensor exhibits a good sensitivity to the relative permittivity, about 13 times as high as the QCM sensor. Figure 4 depicts the frequency shift as a function of liquid electrical conductivity. For the LFE sensor, the sensing range is about 4 times as high as the QCM sensor. The frequency drop saturates finally at about -5.75 kHz, over 125 times as high as the QCM sensor. Besides, we can find a turning point at around 0.1 S/m. This phenomenon also appears in the experiment of Ref [2]. The displacement fields reveal that a mode conversion occurs at this turning point. The displacement field alters from an in-phase shear motion in a slightly eccentric position to an out-of-phase shear motion under the two LFE electrodes.

5. Conclusions

In this paper, we adopted the commercial finite element software, COMSOL, to analyze LFE sensors and further introduced the Stokes model to calculate the sensitivities to the alternations of various liquid properties. Results show LFE sensors not only yield a wider sensing range than QCM sensors, but also exhibit excellent sensitivity to the liquid viscosity, relative permittivity and electrical conductivity, almost 4, 13, and 125 times as high as the QCM sensor respectively. Moreover, the simulation results exhibits similar trend and comparable values with the experimental measurements in literature, verifying the validity of the simulation model proposed in this work.

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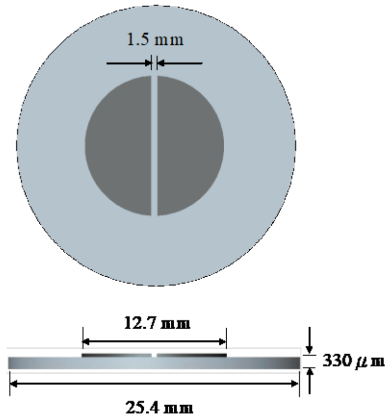

Fig. 1 The schematic of a LFE acoustic wave sensor with the corresponding dimensions.

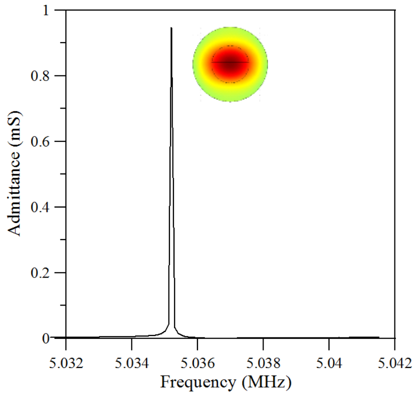

Fig. 2 Frequency response of the pure LFE acoustic wave sensor.

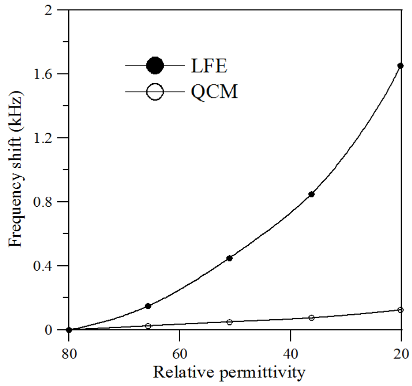

Fig. 3 Sensitivities of the QCM and LFE sensors to the variations of relative permittivity.

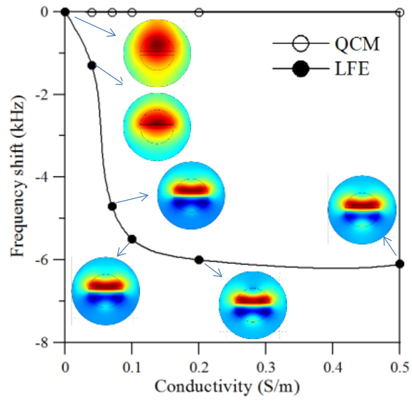

Fig. 4 Sensitivities of the QCM and LFE sensors to the variations of electrical conductivity.