FEA Calculations On The Lateral Field Electroded Sensor

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***Abstract*— Lateral Field Electroded (LFE) sensors may be used to measure the permittivity and conductivity (electrical properties) of liquids in contact with the surface opposite the electroded side. Our previous Finite Element Analysis (FEA) calculations studied these devices for the two quartz boundary conditions of surface-charge-free and grounded. Those results helped sort out which thickness-shear modes were involved. This work expands the calculations to model the effects of changes in the dielectric and conductivity properties of the liquid. Results are presented for the effects of changing either just the dielectric constant or changing the conductivity of water. The calculated results are compared with available experimental results for both 10 MHz plano-plano blanks and 6 MHz plano-convex blanks.**

I. Introduction

A new approach to bio-interface sensing was introduced recently [1] and studied with Finite Element Analysis (FEA) [2]. The earliest device was a 10 MHz plano-plano AT-cut quartz blank with two electrodes on one side that have a gap between them to create a laterally directed electric field in the z' direction , conventionally called Lateral Field Electrodes (LFE). With the electrical field in this direction, excitation can occur for the shear modes typically found in the AT-cut. The two important modes identified with the earlier FEA work were the fundamental mode, the (100), and an anharmonic mode, the (101). It was found that the (100) mode disappeared while the (101) became dominant as the electrical condition on the quartz surface changed from charge-free to grounded. This earlier research led to a 6 MHz plano-convex design that better separates the modes, the (101) being the main mode of interest in practical applications. Changes in the liquid electrical properties, with either the dielectric constant increasing or the conductivity increasing, cause the frequency to move downwards, which provides access to electrical information about the liquid, information heretofore not available to resonant sensors.

The concept is used experimentally by monitoring the frequencies and strength of resonant modes while exposing the surface opposite the electroded surface to liquids of varying dielectric constant or electrical conductivity.[1] The observed frequency shifts are larger than can be expected from liquid viscosity and mass loading effects. This work theoretically explores changes in the frequency of the (101) mode as the electrical properties of the liquid change.

II. Theoretical Development

The original plano-plano device is a 10 MHz fundamental mode AT-cut 14 mm blank with LFE of 7 mm diameter and a 0.5 mm gap on one side aligned to create a lateral field in the z' direction to excite the slow shear mode (C-mode). The 6 MHz plano-convex (1.5 diopter) device has the electrodes on the convex side. The FEA program Comsol was used for the calculations [3].

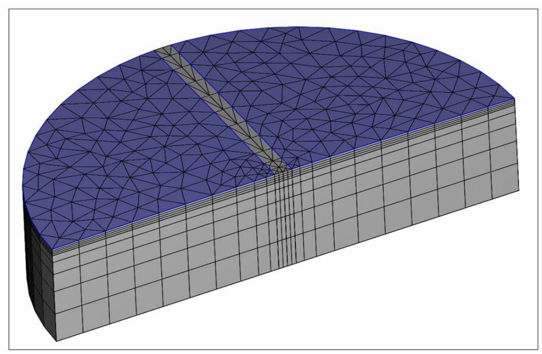

Fig. 1 FEA model of the plano-convex 6 MHz design with a 2.5 mm liquid thickness. Liquid is on the plano side, electrodes are on the convex side.

The model for the 6 MHz device is shown in Fig. 1. The material added to the plano side in Fig. 1 represents the liquid. More recent versions of Comsol allow suppressing the mechanical equations in the added material so that only the electrical properties are included in the calculations. The analysis here leaves out any mass loading effects of the LFE electrodes. Meshing was accomplished by meshing the

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interface surface and then sweeping this mesh both ways. The result is a clean, layered mesh that helps with the modeling of the mechanical motion in the quartz and the penetration of the electrical field into the liquid.

Two different calculations were performed depending on the properties of the liquid. If only the dielectric properties were changing (no conductivity), then an eigenfrequency analysis was performed with the two electrodes grounded to calculate the short-circuit resonant modes. If the conductivity was nonzero, then a frequency response calculation was necessary. In this case, one electrode was driven with 0.5 V and the other electrode was driven with -0.5 V. The resonant frequency was defined in the calculations as the frequency for the maximum real component of the current flowing in the frequency response.

Different experimental configurations were explored. The FEA calculations were performed with either a 5 mm thick liquid or a 2.5 mm liquid. In addition, the free surface of the liquid was held either charge-free or grounded. Calculation of the results for these different conditions helps determine how the experimental configuration might affect results. As will be seen, the results are not very sensitive to these configuration changes for the 6 MHz plano-convex design, but are very sensitive for the 10 MHz plano-plano design.

Since the (101) resonant frequency shifts significantly with changes in dielectric constant , a method devised earlier was used to locate the desired mode in the eigenfrequency analysis results. The ratio of the xy shear energy to the total motional energy, R_{shear}, was calculated and plotted. This ratio is formed by first calculating the total motional energy from the kinetic energy of the mode, E_{total}.

$$E_{total} = \frac{1}{2}\iiint_V (2\pi f_m)^2 * \rho * (u^2 + v^2 + w^2) dV. \quad (1)$$

The xy component of shear energy E_{shear} in the mode can be calculated from the elastic energy as

$$E_{shear} = \frac{4}{2}\iiint_V e_{xy}{}^2 c_{66}^E * dV. \quad (2)$$

Here, e_{xy} is the xy shear strain of the mode and c^E_{66} is the appropriate elastic stiffness coefficient in the plate axes system. The 4 in front of the integral accounts for symmetry in the shear strain. Then, the xy Shear Energy Fraction R_{shear} is given by

$$R_{shear} = E_{shear} / E_{total} . \quad (3)$$

In the case of the frequency response calculations, a broad step frequency response was performed to locate the resonant frequency, then a narrow step frequency response was performed to accurately identify the resonant frequency.

An earlier example [1] of the use of the xy Shear Energy Fraction is shown in Fig. 2. The earlier model had no liquid, but used the two extremes of quartz surface electrical conditions of charge-free or grounded. In Fig. 2, which is for the 10 MHz plano-plano model, we note that the (100) and the (101) modes cross in frequency as the external electrical boundary conditions change between the two extremes. The mode shapes shown in the inserts are poorly trapped and change with the change in the electrical boundary condition.

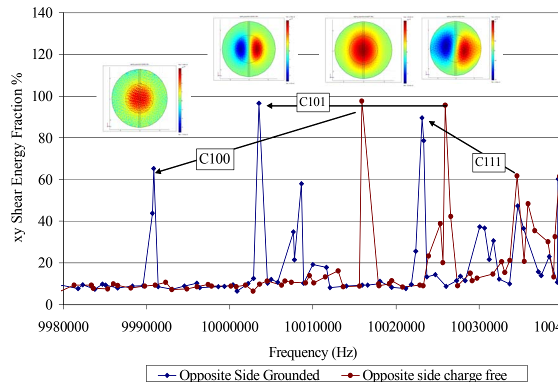

Fig. 2 Earlier calculated results for the xy Shear Energy Fraction for the 10 MHz plano-plano device for the two cases of the quartz surface either charge-free or grounded.

III. RESULTS FOR THE PLANO-PLANO 10 MHZ DESIGN

The previous work emphasized that this quartz blank design has ambiguities in the mode identification when there are changes in the external electrical boundary conditions. Frequency shift data of experiments are difficult to interpret because the (101) mode appears as soon as the relative dielectric constant increases above 1 and the (100) mode begins to disappear, making mode identification and frequency shifts potentially ambiguous. The circumstance chosen here to study is changes in conductivity of water. This is because the (101) mode is already dominant due to the high relative dielectric constant of water. Thus, any frequency changes of this dominant mode are unambiguous.

The available experimental results involve measurement of frequency changes when the conductivity of distilled water is changed by adjusting the wt. % of KCl [4]. Note that the viscosity changes caused by the addition of KCl are very small, so frequency changes due to those viscosity changes are ignored. All frequency shift data is presented after the shift due to the viscosity of the water is subtracted. The conversion constant used for wt. % KCl to conductivity in S/m is 189.73.

The calculated results provide a wealth of information about the changes in the resonant behavior as conductivity changes. An equivalent circuit was selected to account for the fact that the electrical current flowing in the liquid at resonance causes dissipation. Figure 3 shows the equivalent circuit. The R_x is a lumped resistance that represents the distributed dissipation in the liquid. The remaining circuit elements in Fig. 3 are the standard equivalent circuit for a piezoelectric resonance. The current flow in the frequency response calculations was fit to the response equation of this equivalent circuit.

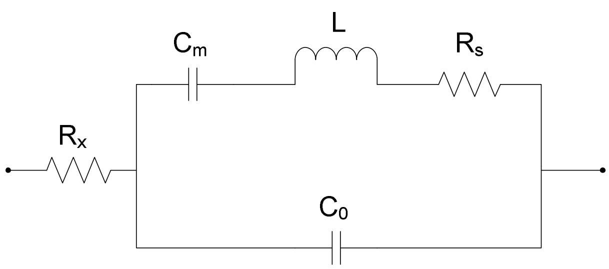

Fig. 3 Equivalent circuit used to model the response of a 10 MHz plano-plano design to changes in conductivity of the liquid

Figure 4 shows the calculated results vs. conductivity for the C_m, R_s, and R_x for the 10 MHz plano-plano model with 2.5 mm of liquid and the free surface of the liquid grounded.

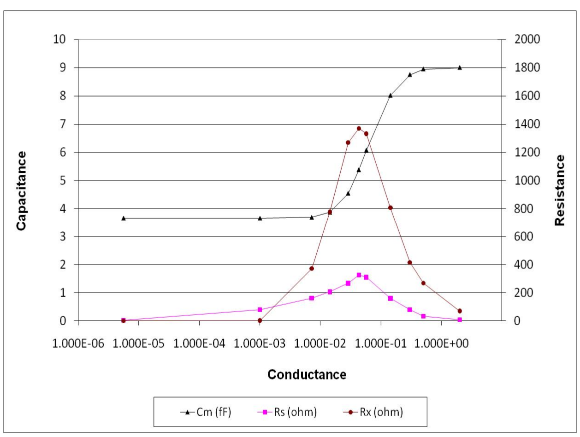

Fig. 4 Calculated results for the equivalent circuit parameters of the 10 MHz plano-plano model for a 2.5 mm liquid with grounded free surface.

We see in Fig. 4 that the R_x and R_s have a peak. This is explained as follows. As the conductivity increases in the liquid, the power dissipation increases linearly with conductance. However, there is a skin effect, so as the conductivity continues to increase, the depth of penetration of the electric field decreases, thus reducing the volume of liquid involved in power dissipation.

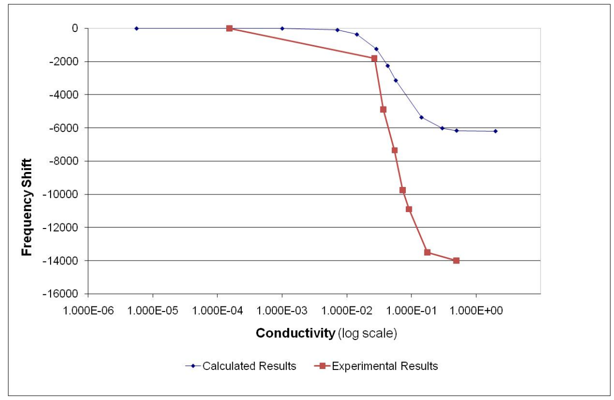

Fig. 5 Experimental and calculated results for the 10 MHz plano-plano blank device for the frequency shifts due to changes in conductivity of water.

Frequency shift vs conductivity results from the calculations are compared to the experimental data in Fig. 5. As seen in Fig. 5, the calculated results and experimental results do not compare very well. Results for using a charge-free instead of a grounded liquid surface, as well as for using a thicker liquid level of 5 mm, compared worse than shown in Fig. 4. Our explanation for this has to do with the shape of the resonant mode being strongly dependent on these external conditions. Also, there may be some mode shape and frequency shift effects due to contact between the quartz blank and the experimental apparatus due to the poorly trapped mode.

IV. Results for the Plano-Convex 6 MHz Design

A plano-convex design, the readily available 6 MHz, 1.5 diopter, 14 mm blank used for thin film thickness monitors, was used for the experiments and for the calculations. It has well-defined mode shapes. The previous analysis on this design showed that the (100) and (101) modes have frequencies that are well separated, the separation in resonant frequency being larger that the predicted shifts in frequency due to changes in either dielectric constant or conductivity.

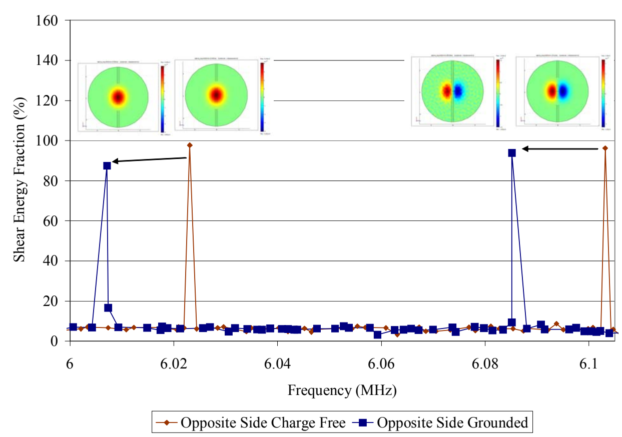

Fig. 6 Earlier calculated results of xy Shear Energy Density vs. frequency for the 6 MHz plano-convex model with the plano side either charge-free or grounded. The results show the excellent mode separation and well-trapped mode shapes.

Figure 6 shows the xy Shear Energy Density in % vs. frequency for this blank design when the opposite surface is either charge-free or grounded.

As can be seen in Fig. 6, the separation between the (100) and (101) resonant frequencies is larger that the frequency shift due to the change in electrical boundary condition. Thus, experimental data from this design are unambiguous. Also, the mode shapes are well trapped and relatively independent of the external electrical situation, and, hopefully, of any contact with the experimental apparatus.

Figure 7 shows the calculated and experimental [1] frequency shifts for changes in dielectric constant. The calculations shown are for a 2.5 mm thick liquid layer. The calculated results for the two cases of charge free and grounded free surface of the liquid layer were within 1% of each other, so only the grounded case is shown. No study of thinner layers was done as it seems more practical to use a thick enough liquid layer to eliminate the effects of the electrical boundary condition on the liquid free surface.

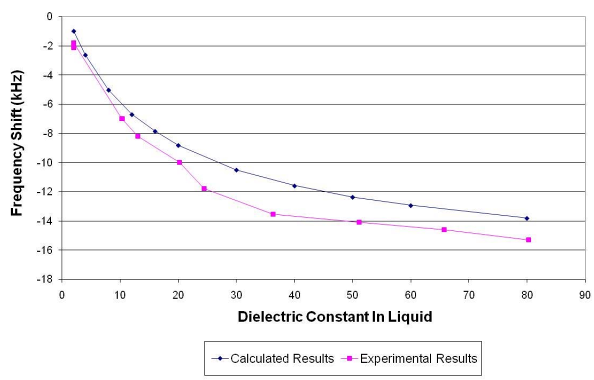

Fig. 7 Experimental and calculated results for the 6 MHz plano-convex blank design for frequency shift vs. changes in dielectric constant.

The results in Fig. 7 show a satisfactory comparison of the experimental data and the calculated results.

At this time, there is no experimental data for the 6 MHz blank design for changes in frequency with changes in conductivity. Calculations were done to provide this information for future experimentation. Figure 8 shows calculated results. Two cases are shown, the water thickness of 5 mm and surface charge free, and water thickness 2.5 mm with a grounded free surface. There is only a small difference in the two cases.

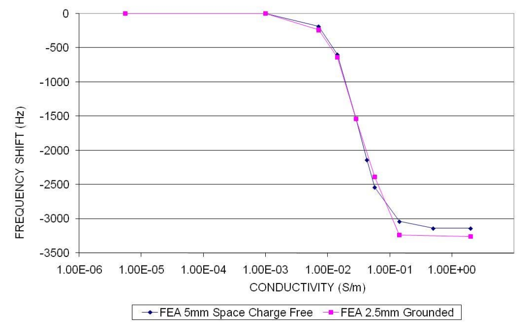

Fig. 8 Calculated results for the 6 MHz plano-convex blank design for frequency shift vs. changes in water conductivity. Two cases, 5 mm thick liquid with space charge free surface and 2.5 mm thick liquid with grounded free surface.

V. CONCLUSIONS

The use of Finite Element Analysis for the Lateral Field Electroded liquid sensor has been extended to include the dielectric and conductivity properties of the liquid. Several cases have been examined. First of all, for the 10 MHz plano-plano blank design, frequency changes with changes in conductivity of water are calculated. The results compare poorly with previously published results. This design is not recommended for experimental applications.

The 6 MHz plano-convex blank design is analyzed for frequency changes for either dielectric constant changes or conductivity changes of water. The results for dielectric constant changes compare favorably with previously published experimental results. The results for conductivity changes of water await some experimental confirmation.

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