Design and Simulation of a MEMS-Based Capacitive Micro-Machined Ultrasonic Transducer for Viscosity Sensing Applications

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Abstract: An analytical and simulation study of a micro electro mechanical systems (MEMS) viscometer is reported. This research presents design considerations and feasibility regarding the use of capacitive micro-machined ultrasound transducer (CMUT), for viscosity sensing applications. This sensor uses circular membranes actuated and sensed electronically. The proposed device works on frequency damping of acoustic waves due to fluid rather than surface acoustic waves (SAW) at the interface of CMUT and the fluid. The sensor is intended to measure viscosity of liquids as high as 150 centipoises for industrial applications.

Keywords: mems, ultrasonic transducer, CMUT, viscosity sensor.

1. Introduction

Piezoelectric crystals, ceramics, polymers, and piezo-composite materials have long dominated ultrasonic transducer technology, especially in rheological applications. In recent years, due to the advancement in micro fabrication techniques, the technology of capacitive micro-machined ultrasonic transducers (CMUTs) has emerged as a competitive technology in the field of viscosity measurements. As the recent development of the MEMS technology, realization of a practical viscosity sensor is becoming more feasible. Viscosity of liquids is a universally important property in a wide variety of industry and research fields. In automotive industry, the status of the engine oil can be evaluated by measuring its viscosity in order to provide proper functionality of the system [1]. In biotechnology area, polymerase chain reaction (PCR) is a most widely used technique for amplifying specific region of a DNA strand for a variety of applications such as DNA cloning, and gene analysis which can be detected by measuring the viscosity variation in real time [2]. In addition, due to the high gas absorbability of Ionic Liquid, gas sensors can be developed by using Ionic Liquid as a sensing material followed by measuring the change in viscosity [3, 4], and that can be used for many applications such as on-line medical diagnosing, environment monitoring and industrial process. Various types of viscosity sensors have been developed.

The most commonly adopted method utilizes the interaction between the fluid and the transmitted acoustic wave, i.e. oscillating structure based detection, in which cantilever beam [5], suspended plate/membrane [6–9] and quartz crystal microbalance [10] structures have been used for sensing purpose. The structures are immersed into the loaded liquid medium during the measurement and actuated to oscillate under their resonant frequency. The interaction of the structure and the fluids of different viscosities results in the application of variable damping onto the oscillating structures. Hence, the resonant frequency and Q-factor of the oscillating structure differ according to the density and viscosity of the loaded liquid. Detection of the resonant frequency shift or the full width half-maxima of the structure frequency response, the viscosity sensing function can be achieved. Although various types of viscometers have been developed in the world, researchers are still investigating novel methods for sensing viscosity as many users are not satisfied with the conventional viscometers from the view point of usability in a long range and portability like the handheld digital multimeter for the electric measurements.

In this paper, a unique strategy dependent on capacitive micro-machined ultrasonic transducer (CMUT) is demonstrated for the monitoring of viscosity which works on the principle of oscillating structure based detection method. As mentioned before, the resonance characteristics of the CMUT device will be a mathematical function of viscous damping and density, therefore the generated ultra-sonic wave can be monitored for measuring the rheological properties of the fluid. Obviously, with this strategy, additional function of viscosity sensing can be easily added to the existed CMUT devices, thus further enhancing the application potential of MEMS technology.

2. Principle of Working

A novel CMUT based micro-viscosity sensor is designed as shown in the Figure 1, two CMUTs one transmitter and other receiver are subjected in a vertical column facing each other with fluid in inspection between them. The mechanical performance and resonant characteristics of receiver CMUT changes by the viscosity of its surrounding fluid medium, due to the damping effect of the liquid. Thus, affecting the ultrasonic signal generated at the receiver, under same driven conditions of pulse excitation.

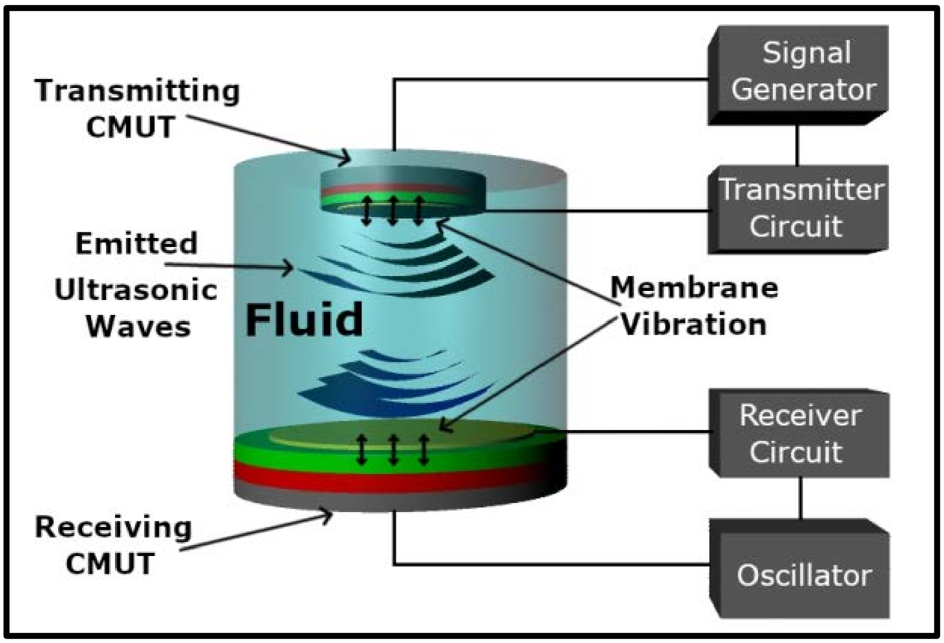

Figure 1. Schematic diagram of the working and measurement principle of the MEMS-based viscosity sensor.

The sensor is based on excitation of a free acoustic mode description of an isolated transmitter CMUT, which in turn is coupled to the receiver CMUT via the fluid under assessment. The receiver CMUT picks up the signal in time domain. Processing this signal and applying a Fourier transform, a frequency response is generated. The frequency response is correlated to the viscosity of the fluid. Thus, viscosity information could successfully be extracted from this device. Sharp resonances are shown to occur that could be significantly helpful in measuring the viscosity.

3. Simulation Methods on COMSOL Multiphysics

COMSOL Multiphysics is used to model the complete functionality of the proposed sensor. The entire model seeps through various domains of physics like Electronics, Structure Mechanics and Fluid Mechanics. In COMSOL Multiphysics interaction of all the above-mentioned physics is not available. Hence, simulating the entire sensor in one go is not possible, secondly splitting the simulation helps to debug results and troubleshoot through problems and errors more efficiently, thirdly this potentially saves computation time. Time domain and frequency domain studies were computed depending on the results required. As the device was axis symmetric, a 2D axis symmetric geometry was used to reduce simulation time and have a 3D idea of the simulation results.

3.1. Computation of CMUT Parameters

The basic structure of a CMUT is as shown in the Figure 2 (A) and Figure 2 (B). The sensor consists of two types of CMUT. One for transmitting an actuated impulse wave in the fluid column and second, the receiver for sensing the signal generated. The transmitter can have a higher spring constant, high pull in voltage as voltage applied on transmitter side is higher whereas for the sensing purposes lower value of spring constant is required for better sensitivity.

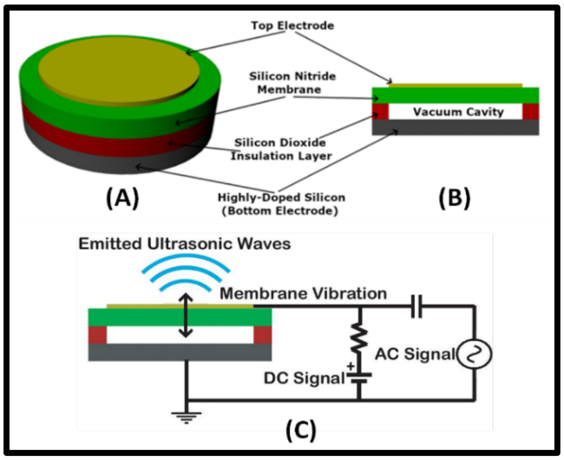

Figure 2. Schematics of capacitive micro-machined ultrasonic transducer (A) Orthographic view. (B) Cross-sectional view. (C) Actuation circuit of the ultrasonic transducer.

A CMUT necessarily consists of two electrodes separated by a non-conducting medium between it. The bottom electrode of the CMUT is a highly-doped Silicon wafer. The two electrodes are separated by an insulating layer of Silicon Dioxide. The functional membrane layer which determines the characteristics of the CMUT is chosen to be made from Silicon Nitride due to its material properties. The CMUT structure is simulated using an 2D axis symmetric modelling using **Solid Mechanics Physics** and parameters were found to have first mode of natural frequency between 40 MHz to 50 MHz as shown in Figure 3 (A) and 3 (B), with pull in voltage well above operating voltages. The parameters simulated for the same are as follows:

Parameters	Transmitter	Receiver
Resonance Frequency	40 – 50 MHz	40 – 50 MHz
DC voltage	30V	10V
AC voltage	5V V_{pp}	-
Membrane Thickness	100 nm	400 nm
Membrane Diameter	5.85 µm – 6.35 µm	11.65 µm - 13 µm
Vacuum Cavity	0.1 µm	0.5 µm
Pull-in voltage	67 v	> 67

Table 1. Optimized dimensions of the simulated viscosity sensor.

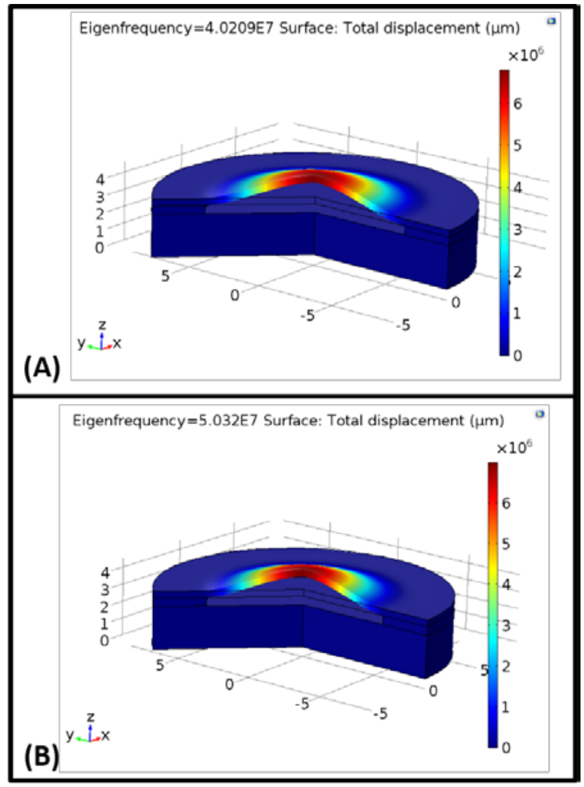

Figure 3. Simulation results of first Eigen mode resonant frequency of the capacitive micro-machined ultrasonic transducer in the working range of (A) 40 MHz to (B) 50 MHz

3.2. Actuation of Transmitter CMUT

The actuation of transmitter CMUT is simulated using **Electro Mechanics Physics.** The transmitter CMUT is located at the top of the vertical column in the sensor; to negate the effect of fluid on the transmitter. The CMUT is operated by applying a DC voltage of 30 V superimposed with an AC voltage 5 V peak to peak of frequency equal to half of the resonant frequency, whose circuit schematics is shown in Figure 2 (C). DC voltage is applied to decrease the spring constant of the plate and secondly to increase the pressure difference created on the top of the circular membrane of transmitter CMUT. Peak displacement of the center of the circular membrane is noted to use in further simulations. The time response shows the deflection of the transmitter membrane and frequency response of transmitter CMUT shows the CMUT to be vibrating at its natural as shown in Figure 4 (A) and Figure 4 (B) respectively, and this is used to generate pulse excitation for receiver CMUT at ultrasonic frequency.

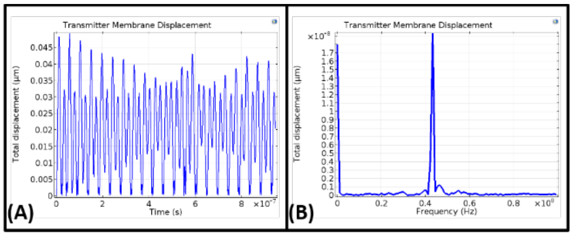

Figure 4. (A) Time variation of the transmitter membrane displacement and the corresponding (B) frequency response calculated using Fast Fourier Transform.

3.3. Generation and Transmission of Pressure Wave

The generation and transmission of pressure wave in liquid column is studied through **Acoustic Structure Interaction Physics** in COMSOL. From the previous simulation result we were able to compute the maximum deflection of the membrane at the center of CMUT membrane. To simulate the entire sensor, we need to note the pressure generated by the transmitter CMUT and the pressure transmitted onto the receiver CMUT. For a CMUT with a circular plate, an equivalent spring constant, mass and damping coefficient can accurately capture the plate's mechanical properties over its entire range of stable detection. The pressure P_C on the circular membrane includes the electrostatic force F_E resulting from the voltage applied to CMUT and the force form atmospheric pressure P_O which is given by [11],

$$\boldsymbol{P_C = P_O + \frac{F_E}{\pi R^2}}$$

The plate's deflection as a function of radial position, r, plate radius, R, and the plate material's flexural rigidity, D, is given by,

$$\boldsymbol{w(r) = \frac{P_O R^4}{64D}\left[1 - \frac{r^2}{R^2}\right]^2}$$

In the equation of plate's deflection, flexural rigidity D is given by the equation, where t is the plate thickness and E and v are the material's Young's modulus and Poisson ratio respectively.

$$\boldsymbol{D = \frac{Eh^3}{12(1 - v^2)}}$$

This is evident from the figure that at r = 0 the plate deflection is maximum.

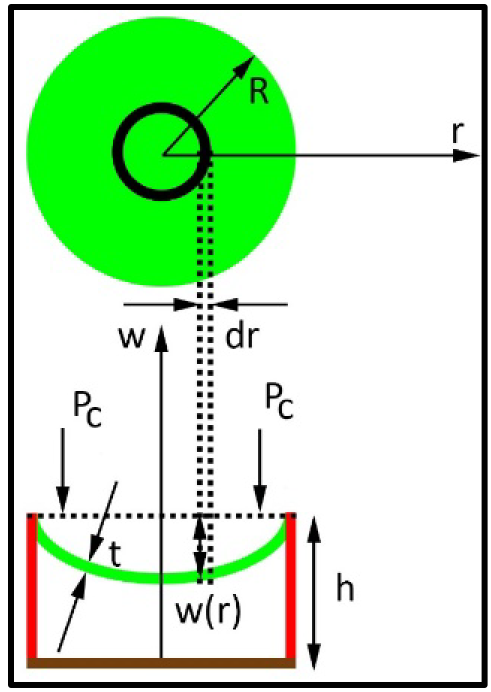

Figure 5. Mathematical demonstration of an ideal circular plate capacitive micro-machined ultrasonic transducer.

$\boldsymbol{P_E}$ is the pressure applied by the electric field onto the membrane, for the shape shown in the Figure 5, the capacitance generated between a small element of thin film membrane of length dr and bottom electrode is given by,

$$\boldsymbol{dC = \int_0^R \frac{2\pi r \varepsilon_0}{g_o - w_{pk}\left(1 - \frac{r^2}{R^2}\right)^2} dr}$$

Integrating the above equation gives the total capacitance between the thin film membrane and the bottom electrode where w_{pk} is the peak displacement of the membrane i.e. *w(0)* and is given by,

$$\boldsymbol{C = \frac{\varepsilon_0 \pi R^2 \tanh^{-1}\sqrt{\frac{w_{pk}}{h}}}{\sqrt{h w_{pk}}}}$$

After several steps of calculation, the relation among the biased voltage V, the ratio x of the central deflection to the effective gap distance, and the ratio α of the pressure inside the cavity to the ambient pressure can be defined as, $\boldsymbol{V(x)}$ which is equal to

$$\boldsymbol{\sqrt{\frac{4h^2 x\left[\left(\frac{64\pi D h}{R^2}\right)x - \left(1 - \left(\frac{\left(1 - \frac{W_{pk}}{3h}\right)}{\left(1 - \frac{x}{3}\right)}\right)\alpha\right)P_O \pi R^2\right]}{3\varepsilon_0 \pi R^2\left(\frac{1}{1 - x} - \frac{\tanh^{-1}\sqrt{x}}{\sqrt{x}}\right)}}}$$

Using the equation above we get a relation between the central displacement maxima w_{pk} and the instantaneous voltage applied *V(x)* and we know the displacement of the entire membrane if we know the peak displacement by equation (mention equation number). The radial displacement was give as a prescribed displacement in COMSOL simulation file. This induced pressure wave in the liquid column and the time variation of pressure generated is shown in Figure 7 (A)-(F). From the simulation, it can be calculated that the pressure received at the receiver is approximately 100 MPa.

3.4. Applying Impulse Signal on Receiver CMUT

This study if performed by using **Solid Mechanics Physics**. Applying an impulse boundary load equal to the load imparted by pressure wave in the last section at the end of the vertical column. We check the output displacement of the center point of the receiver membrane. Time and frequency response of the displacement is plotted and shown in the Figure 6 (A) and Figure 6 (B) respectively.

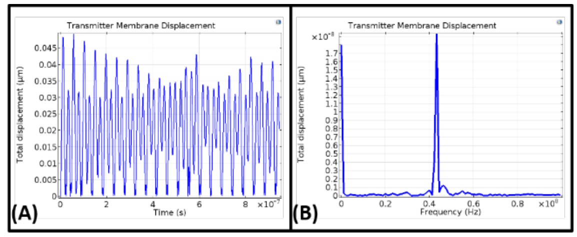

Figure 6. (A) Time variation of the receiver membrane displacement biased at zero DC voltage which is excited in vacuum by the pulse signal generated by the transmitter capacitive micro-machined ultrasonic transducer and the corresponding (B) frequency response calculated using Fourier transform.

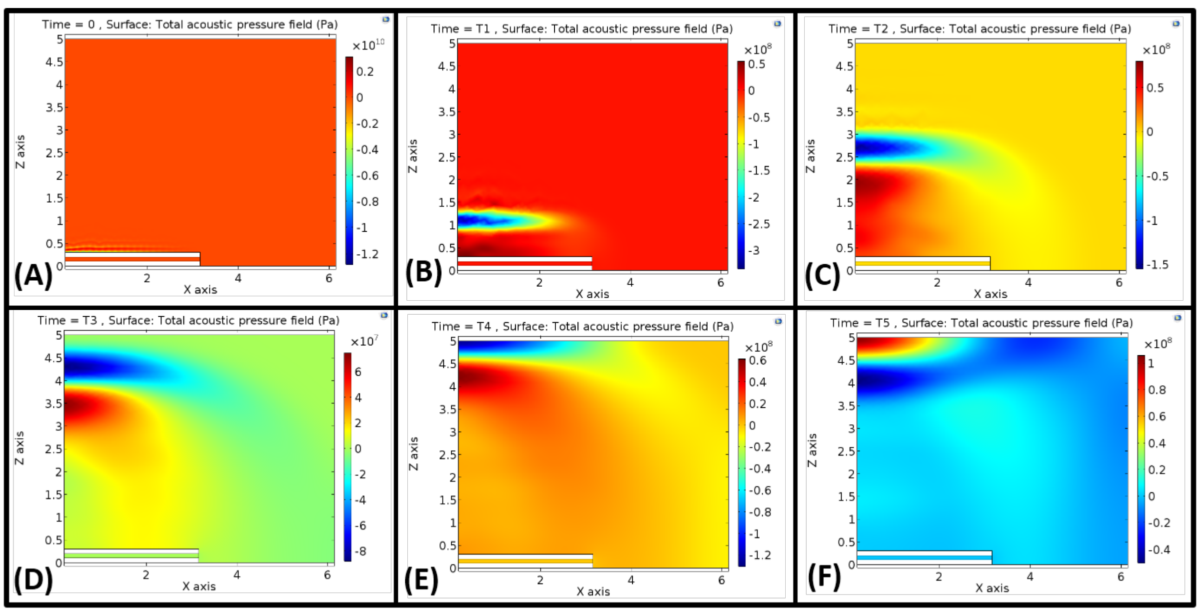

Figure 7. Simulated distribution of pressure inside the liquid column generated due to the pulse excitation of transmitter capacitive micro-machined ultrasonic transducer at time (A) t = 0. (B) t = T_1. (C) t = T_2. (D) t = T_3. (E) t = T_4. (F) t = T_5. ($T_5 > T_4 > T_3 > T_2 > T_1 > 0$)

The results prove that when an impulse wave hits the receiver membrane it vibrates its natural frequency thus we could further use this method to check sensing mechanism of the receiver.

3.5. Signal sensing in receiver CMUT.

The signal sensing capability of the receiver CMUT is studied using **Electro Mechanics Physics**. The CMUT is used with a constant charge on the plate. A potential of 10 V DC is applied across the receiver electrodes and the potential is removed once the capacitor is fully charged. Then an impulse boundary load is applied on the receiver membrane as done in the previous section. The variation in the displacement of the center point of the receiver membrane and change in output voltage is plotted and is shown in Figure 8 and Figure 9 respectively. The change in output voltage is as high as 1 V peak to peak which can be measured externally.

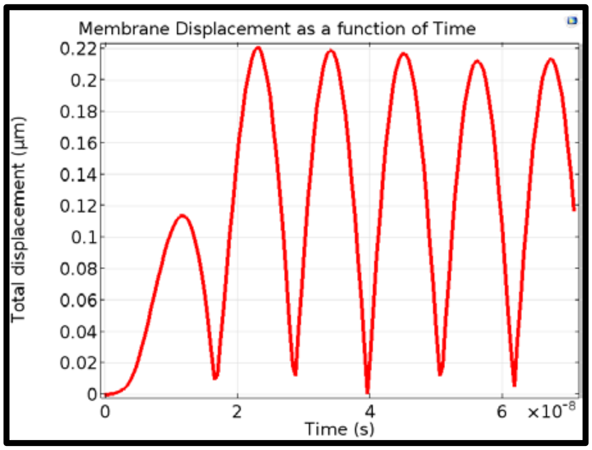

Figure 8. Time variation of the receiver membrane displacement having 10V DC biased-voltage which is excited in vacuum by the pulse signal generated by the transmitter capacitive micro-machined ultrasonic transducer.

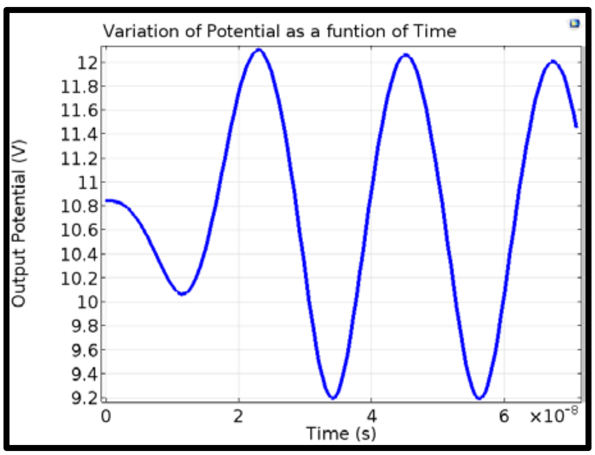

Figure 9. Time variation of the receiver membrane output potential having 10V DC biased-voltage which is excited in vacuum by the pulse signal generated by the transmitter capacitive micro-machined ultrasonic transducer.

3.6. Change in Frequency Response of the Receiver CMUT in Different Fluids

Acoustic Structure Interaction Physics is used to calculate the frequency response of the receiver CMUT. The frequency responses corresponding to different fluidic medias are shown in Figure 10 (A)-(E) and it is evident that the frequency response depends on the rheological properties of fluid. After confirming that the Sensor as a module can work and give a feasible output we use COMSOL to plot how an interfacing fluid medium affects the frequency response. A membrane of given dimensions as that of receiver membrane is immersed in a liquid and the change in quality factor is recorded. The frequency response is calculated by taking the Fourier transform of the time domain signal generated at the receiver end. The most important thing to note here is that while recording the time domain signal the sampling rate must be higher than the twice of the maximum frequency present in the signal which is termed as Nyquist rate, so for better efficiency the sampling rate must be as high as possible.

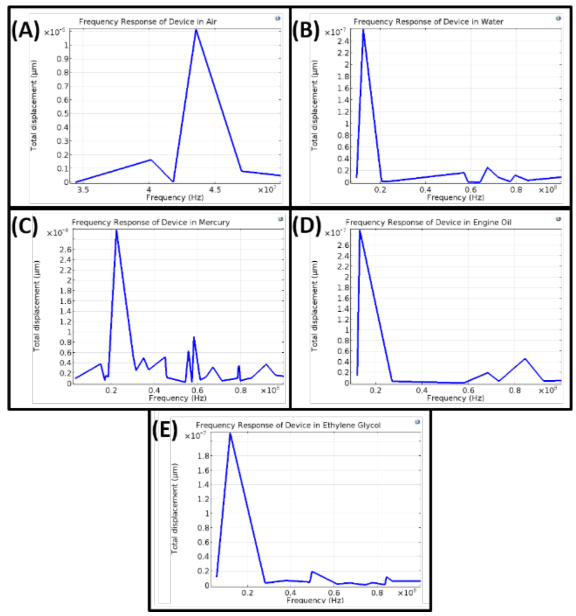

Figure 10. Frequency response of the viscometer in different fluidics media. (A) Air. (B) Water (C) Mercury. (D) Engine Oil. (E) Ethylene Glycol.

4. Results and discussion

The change in quality factor is a dependent function on the viscosity of the liquid. A graph with viscosity and quality factor is plotted as shown in Figure 11, to see the response of the sensor. Different mathematical fitting models are also compared in the Figure 11 and it can be concluded that the exponential model represents the best fit. Using COMSOL Multiphysics we get an idea of how a structure behaves in a given condition. MEMS devices are fabricated using micro fabrication techniques which requires a lot of time and is quite costly. However, with simulation we can tweak our devices and comment about the performance without actually making them, but a lot of precaution and care must be while designing our simulation.

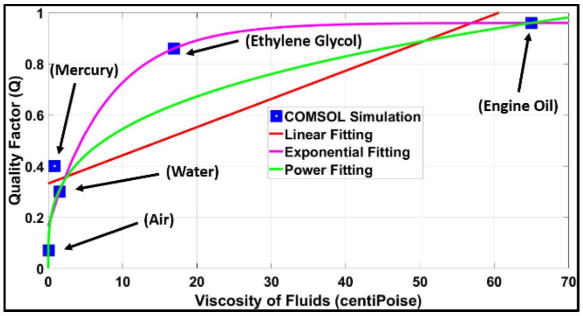

Figure 11. Curve fittings for the variation of the quality factor corresponding to the frequency response of the viscometer in different fluidic media.

5. Conclusion

A novel CMUT based micro viscosity sensor is presented. The frequency response of CMUT will be affected by the viscosity of fluid in contact with it due to the resultant damping effect. Given the same driven condition, the ultrasonic signal generated from the receiver CMUT will also be changed accordingly. Through detecting the damped ultrasound signal transmitted in the fluid in time domain followed by performing Fourier transform, the frequency response of the receiver CMUT can be obtained. From the value of center frequency shift and full width half maxima of the signal, information about the viscosity and density of surrounding medium can be extracted. Considering the operation principle, the currently proposed viscosity sensor can be easily used to achieve in-situ viscosity measurement through immersion operation without requiring additional sample preparation and also suitable for application in certain cases with rigorous environment. Through adding reference surface design for acoustic wave transmission calibration, additional functions such as acoustic based structure health monitoring and dimension measurement can also be realized with the same device, enhancing its versatility.

6. References

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