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A Micro-acoustic Wave Sensor for Engine Oil Quality Monitoring

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Abstract – **A micro-acoustic wave sensor based on the thickness shear mode (TSM) quartz resonator has been investigated for engine oil quality monitoring through the viscosity measurement. Effects of the fluid mechanical and electrical properties on the TSM resonator with both sides in contact with the fluid have been studied and compared to the 1-sided device. Sensor prototypes based on both the 1- and 2-sided TSM resonators have been developed and tested in various fresh and used engine oils.**

I. Introduction

Engine oils are complex, highly-engineered fluids designed to allow proper engine performance over a long service life. An oil that meets this goal performs a variety of protective and functional jobs in addition to providing a hydrodynamic film between moving components, which include removing heat, suspending contaminants, neutralizing acid, preventing wear and corrosion, etc. However, the engine oil has only a finite life as the fluid chemical and physical properties change and ultimately degrade during use. When the oil reaches the end of its useful life, it must be removed and replaced with fresh oil in order to maintain engine protection. The quality/condition of the engine oil is a measure of the oil's ability to perform the above functions that determines the residual useful life of the oil.

Depending on engine types, operating conditions, oil formulations, etc., the engine oil degrades in a variety of different ways, which makes it very difficult for real time oil quality monitoring to determine when to change oil. For this reason, most engine operators, for example passenger car owners, usually change oil at a constant time or mileage interval according to the recommendation of the engine or vehicle original equipment manufacturers (OEMs). However, since the decision for the oil change is not based on the real oil condition of the specific engine, the oil could be changed before reaching the end of its useful life, or after its useful life is exceeded. This could cause wasting oil and money or reducing the engine life. To help operators better determine when to change oil, some OEMs, especially passenger car OEMs, have developed algorithm based systems that monitor engine operating-parameters such as engine revolutions, oil temperature, fuel usage, etc., to better "estimate" oil condition. While a step in the right direction, this type of algorithm is still not based on actual oil condition. Off line laboratory analysis has been used in certain applications such as highway diesel trucks, where the residual useful life of the oil is determined by a series of laboratory tests. A problem with this method is the inconvenience, expense and potential time lag associated with taking oil samples and waiting for laboratory results. Therefore, an on-board oil quality monitoring system based on direct measurement of oil physical or chemical parameters could bring not only economic benefit through reducing service cost and equipment down time, but also benefits the environment through maximizing the use of engine oils [1- 3].

Due to large variations in oil formulations and oil degradation modes, current laboratory tests of the engine oil quality usually include measurement of a number of oil parameters such as the viscosity, permittivity/conductivity, soot, total base number /total acid number, oxidation, nitration, water concentration, etc. For on-board oil quality monitoring, permittivity type (capacitive) and viscosity sensors have been mostly reported [4 – 7]. Even though it is almost impossible for any single sensor principle to provide complete oil condition information, viscosity measurement is particularly useful in providing general and sometimes critical indication of the oil condition when the oil is close to the end of its useful life. Many oil failure modes can be identified through the oil viscosity together with other oil parameters measurement. Therefore, viscosity sensor is an important part of the potential oil quality sensor system especially in applications where the viscosity change is the main result of oil degradation.

Micro-acoustic wave sensors which include the bulk acoustic wave (BAW) and surface acoustic wave (SAW) sensor have been widely investigated for fluid property such as viscosity measurement for the last two decades [8, 9]. Compared to other viscosity sensors, the advantage of the micro-acoustic wave sensor is the potential small size, low cost, high accuracy and intrinsic digital signal output, which makes it much more attractive for on-line viscosity measurement. The BAW sensor based on the thickness shear mode (TSM) in quartz is one of the most commonly used micro-acoustic wave devices for fluid viscosity measurement [10-12] and the mechanism of the sensor interacting with fluids, mass and viscoelastic layers has been well studied and understood [13 - 15]. However, in almost all these investigations, quartz resonators with only one electrode in contact with the fluid was used and the fluid is primarily aqueous solutions or simple fluid systems like solvents. There are very limited reports [16] of using quartz

TSM sensors for engine oil applications and the response of the sensor to the property change of the engine oil has not been well understood.

In the present study, the impedance of the quartz TSM sensor with one and both electrodes in contact with fluids has been tested and compared. Influence of the fluid mechanical and electrical properties on the sensor's series resonant frequency, motional resistance and the parallel capacitance has been studied. Test results of the TSM sensor prototypes for oil viscosity measurement have been reported for both new and used engine oils.

II. Quartz TSM Resonator with Both Electrodes in Contact with Fluids

Shortly after Nomura and Okuhara found that the quartz resonator could operate in aqueous solutions with one electrode in contact with the fluid (1-sided TSM sensor) in the beginning of 1980s, they also found that the device could oscillate in some organic solvents with both electrodes in contact with the fluid (2-sided TSM sensor) [17]. However, due to the fact that the 2-sided TSM sensor could not work in conductive fluids and the higher liquid damping caused larger signal noise in non-conductive fluids, very little following up work was conducted by researchers at that time on the 2-sided TSM sensor, who instead chose to use the 1-sided device for their mostly aqueous solution measurement [18]. Several years later, Yao tested the 2-sided TSM sensor with more fluids and confirmed some of the results Nomura obtained [19, 20]. Since then, for more than one decade, almost no work could be found published on the 2-sided TSM sensor while in the same time the 1-sided TSM sensor has received extensive investigation for numerous applications.

While the pioneer research on the 2-sided TSM sensor in the early 1980s is significant and even revolutionary, the investigation itself is quite incomplete and the test results are sometime confusing due to the limitation of the available sensor driving electronics and the understanding of BAW sensor theory [17, 19-21]. In these studies, all tests were conducted using some very simple oscillators like single transistor or TTL oscillators. The output of the sensor was found to be significantly influenced by the oscillator type [20, 21], testing cell grounding and compensation capacitance [20], which makes it very difficult to compare results obtained by different research groups. In addition, some unusual behaviors were observed for the sensor operating in fluids. For example, it was found that each tested fluid had a critical temperature below which the sensor stopped operating and some fluids resulted in a frequency change in the opposite direction [20]. It is clear from today's understanding of the TSM sensor technology that many of these unusual behaviors come from the driving electronics and not from the TSM resonator. Therefore, it would be very important to re-study the 2-sided TSM sensor with the well established modern impedance analysis method, which could provide the complete sensing information of the device itself without any influence from the driving electronics.

The equivalent circuit of the 2-sided TSM resonator in fluids was reported previously [22] and is shown in Fig.1 (a). R, C_1 and L form the motional arm of the resonator. C_0 is the static capacitance and R_L, C_L arise from the fluid electrical properties, namely the conductivity and permittivity. When the 2-sided TSM resonator operates in non-conductive fluids (R_L=∞), the equivalent circuit model reduces to the form shown in Fig.1 (b), where the parallel capacitance, C_0^*, is the combination of C_0 and C_L. It should be noted that the circuit model in Fig. 1 (b) shares the same form as the 1-sided TSM resonator in fluids.

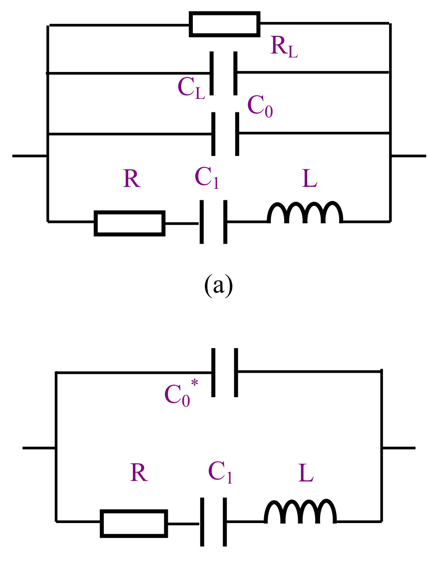


Fig. 1. The equivalent circuit model of the 2-sided TSM resonator in fluids. (a) General form. (b) In non-conductive fluids.

The series resonant frequency for both the 1- and 2-sided TSM quartz resonator is:

$$f_s = 1/2\pi\sqrt{LC_1} \quad (1).$$

Hence, the fluid permittivity, which is related to C_L, has no effect on the series resonant frequency of the device. The parallel capacitance of the 2-sided TSM resonator in non-conductive fluids, C_0*, however, will change as the fluid permittivity changes.

For the 1-sided TSM resonator operating at the fundamental frequency, it has been found that [23, 24]

$$\Delta f_s = -f_s^{3/2}(\rho\eta/\pi\rho_q\mu_q)^{1/2} \quad (2) \text{ and}$$

$$\Delta R = (\pi\rho\eta/f_s\rho_q\mu_q)^{1/2}/8k_0^2C_0 \quad (3).$$

Here ρ and η are the fluid density and viscosity respectively, ρ_q and μ_q are the quartz density and shear modulus respectively; and k_0^2 is the electro-mechanical coupling coefficient of the substrate. Eqn. (2) and (3) indicate that the fluid electrical property change has little effect on the series resonant frequency and the motional resistance of the 1-sided TSM sensor.

For 2-sided TSM resonator operating in non-conductive fluids, it has been suggested that the sensitivity of the series resonant frequency and the motional resistance to the change of the fluid density and viscosity product is 2 times higher than that of the 1-sided TSM sensor due to the increased loading effect. However, no experimental data was offered [22].

For the 2-sided TSM resonator operating in conductive fluids, it can be seen from Fig.1 (a) that the R_L decreases with increasing fluid conductivity and would eventually short the two electrodes of the device. Previous works have shown that the resonant frequency of the 2-sided device changes linearly with the fluid conductivity within certain ranges [20, 21]. However, for most of aqueous solution applications, the fluid conductivity is beyond this range and it would be difficult for the 2-sided device to work in these applications.

III. Experimental

AT-cut 5 MHz quartz TSM resonators obtained from Maxtek Inc. (USA) were used in the study. An Agilent 4294A precision impedance analyzer was used to measure the impedance of the device in different fluids at room temperature. The elements of the equivalent circuit model of the resonator were obtained through the curve fitting of the measured impedance. Each fluid was tested twice and the average was reported.

Sensor prototypes based on the 1- and 2-sided TSM resonator were developed and tested in various engine oil samples at different temperatures. The viscosity and the density of the oil sample were obtained using a commercial capillary viscometer and density meter. The temperature coefficient of the sensors was tested in a self-made heating cell.

IV. Results and Discussions

A. Impedance Analysis of the 2-sided TSM Resonator

The impedance magnitude and phase of the 2-sided TSM resonator in air, water and an oil viscosity standard are shown in Fig. 2 (a) and (b). The oil viscosity standard has a much lower permittivity and higher viscosity than water. Relative to air, the impedance curve of the resonator in the oil shifts to lower frequency while the impedance peak becomes much flattened. This response is typical for TSM resonators subject to mechanical damping effect and indicates that the device is affected primarily by the fluid mechanical property changes. Relative to air and the oil, the impedance of the resonator in water has a substantial base line shift in the impedance magnitude and the frequency distance between the minimum and maximum impedance decreases. This response is quite different from the 1-sided TSM resonator [15, 25] and indicates that the parallel capacitance of the resonator increases significantly as the fluid permittivity increases.

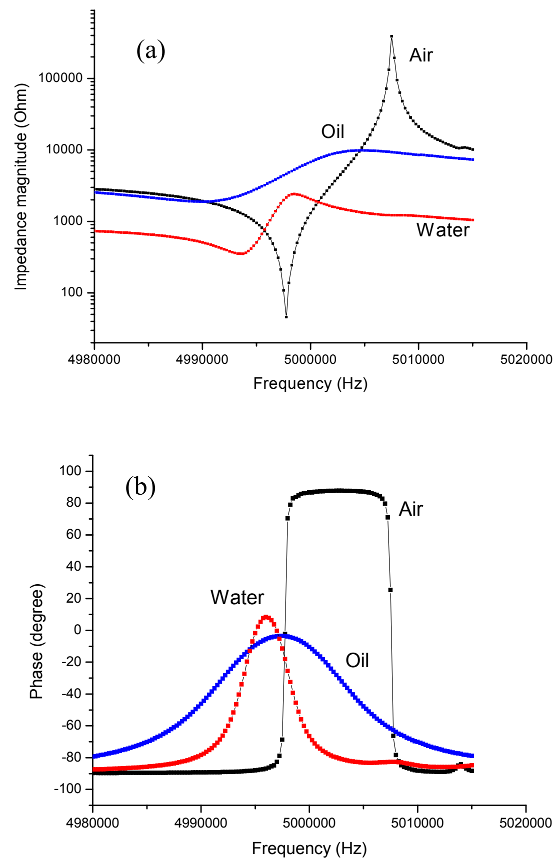


Fig. 2. The measured impedance magnitude (a) and phase of the 2-sided TSM resonator in air, water and an oil viscosity standard.

Table 1 lists fluid samples tested for comparing the 1- and 2-sided TSM resonators. The viscosity and the permittivity of these fluids range approximately from 0.3 cP (Hexane) to 40 cP (Propylene Glycol) and 1 (air) to 78 (water), respectively [26].

TABLE I
FLUID SAMPLES TESTED IN THE STUDY

Number	Samples
1	Air
2	Hexane
3	2-Propanol
4	n-Hexanol
5	1-Octanol
6	Propylene Glycol
7	Ethylene Glycol
8	Distilled Water

The determined parallel capacitance, C_0^*, of each fluid is plotted in Fig. 3 as a function of the fluid permittivity. It can be seen that the parallel capacitance of both the 1- and 2-sided devices increases as the fluid permittivity increases. For the 1-sided device, the change of the parallel capacitance is mainly due to the fringing field effect and signal output begins to saturate for fluids with the permittivity above 20. For the 2-sided device, the change of the parallel capacitance is mainly caused by C_L changing with the fluid permittivity, and very little output saturation is observed over the permittivity range tested. The much higher parallel capacitance of the 2-sided device in high permittivity fluids than the 1-sided device explains the measured impedance of the 2-sided device in water shown in Fig.2. This result suggests that more capacitance compensation is needed in designing oscillators for 2-sided TSM sensors.

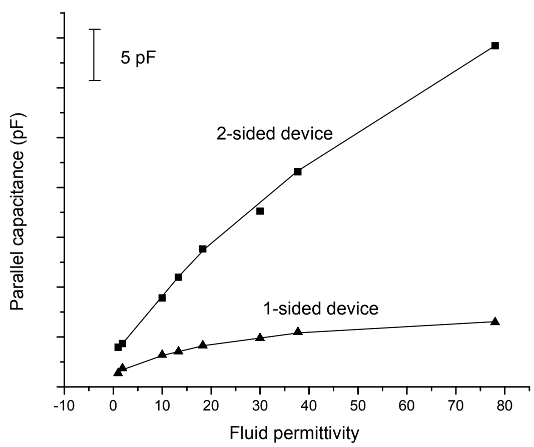


Fig. 3. The parallel capacitance as a function the fluid permittivity.

The determined motional resistance, R, is plotted in Fig.4 as a function of the square root of the fluid density and viscosity product ($\sqrt{\rho\eta}$). It can be seen that the R of the both devices changes linearly with $\sqrt{\rho\eta}$ and the 2-sided device has larger motional resistance than the 1-sided device in the same fluid. This indicates that the 2-sided sensor suffers more fluid damping effect and, therefore, may operate over a smaller viscosity range than the 1-sided sensor. The sensitivity of the motional resistance for the 2-sided resonator is only about 1.3 times larger than that of the 1-sided device which is smaller than the suggestion of [22]. One reason for this difference may be the non-symmetric electrode geometry of the resonator used in this study. However, further theoretical and experimental work is needed to study this issue.

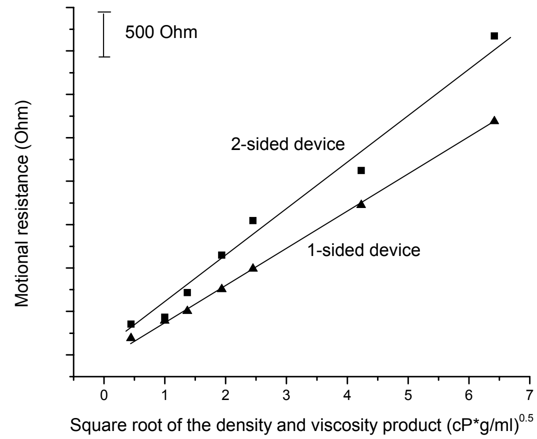


Fig.4. The motional resistance as a function of the square root of the fluid $\sqrt{\rho\eta}$.

Due to the larger fluid damping effect, the maximum impedance phase angle of the 2-sided resonator in most of the tested fluids is below 0°, making it impossible to derive the series resonant frequency of the device. Since the frequency at the minimum impedance, f_{min}, is usually very close to the series resonant frequency of the TSM resonator, f_{main} is used in the present study to compare the sensitivity of the two sensors. Fig.5 shows the change of f_{min} as a function of $\sqrt{\rho\eta}$. It can be seen that the Δf_{min} dependence on $\sqrt{\rho\eta}$ is relatively linear for both devices and the sensitivity of the 2-sided device is about 2.3 times higher than the 1-sided device, which is close to the suggestion of [22]. This result indicates that the sensitivity of the series resonant frequency of the 2-sided TSM resonator could be larger than that of the 1-sided TSM sensor. The fluid permittivity was found to have no clear effect on the sensor's response, which agrees with the above theoretical analysis.

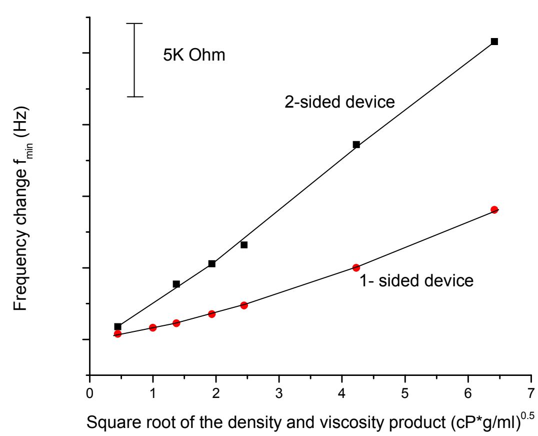
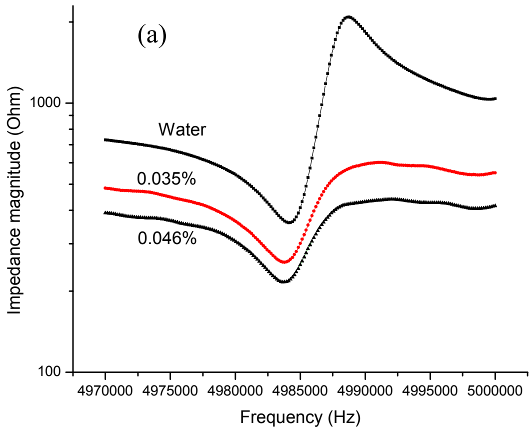


Fig.5. The change of f_{min} as a function of the fluid $\sqrt{\rho\eta}$.

To study the influence of the fluid conductivity on the 2-sided TSM sensor, 0%, 0.035% and 0.046% $CaCl_2$ water solutions have been prepared and tested with the 2-sided TSM resonator. The measured impedance magnitude and phase are shown in Fig. 6 (a) and (b). As the fluid conductivity increases, the direct feed through, R_L, between the two electrodes decreases. When R_L becomes much smaller than the parallel impedance of the resonator, the parallel impedance peak of the resonator vanishes. Therefore, it can be concluded that the 2-sided TSM resonator is not suitable for measurement in conductive fluids.



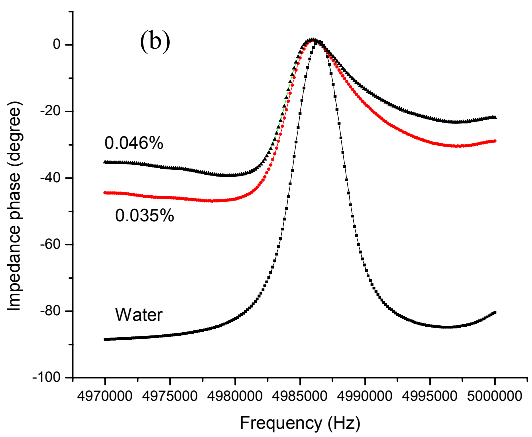


Fig.6. The measured impedance magnitude (a) and phase (b) of the 2-sided TSM resonator in dilute $CaCl_2$ solutions.

B. Sensor Prototype Development and Test

Prototype sensors based on the 1- and 2-sided TSM resonator have been developed and tested with different engine oil samples. Fig.7 shows the response of the sensors to a fresh engine oil sample at different temperatures. Since the temperature coefficient of the prototype sensors was tested to be very small, temperature effect on sensors response was neglected in the study. It can be seen that both prototype sensors have essential linear response to the fluid $\sqrt{\rho\eta}$ and the 2-sided sensor prototype shows a larger signal output due to the larger liquid damping effect. The sensitivity (slope) of the 2-sided sensor prototype is only slightly greater than the 1-sided sensor prototype indicating that the oscillator used in the prototype sensors may have influenced the sensor's response.

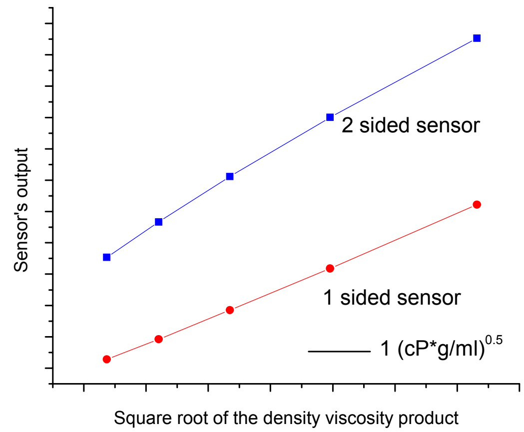


Fig.7. The response of the sensor prototypes to a fresh engine oil

To test the influence of the fluid permittivity on the 2-sided sensor prototype, several non-oil samples with different levels of permittivity were tested along with two oil samples. The sensor output as a function of the fluid $\sqrt{\rho\eta}$ is plotted in Fig.8. Despite the large permittivity variation of the non-oil samples, the response of the sensor is linear with $\sqrt{\rho\eta}$ for all samples. This shows that the influence of the fluid permittivity on the 2-sided sensor prototype is insignificant. However, tests with $CaCl_2$ solutions found that the prototype could not oscillate even with very low salt concentrations.

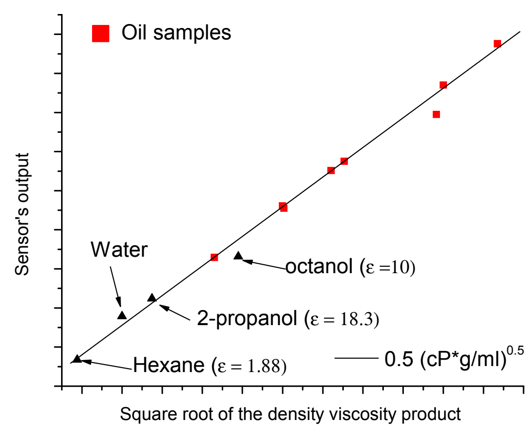


Fig.8. The response of the 2-sided sensor prototype to both oil and non-oil samples

To study how the prototype sensors respond to used oils, a series of oil samples were obtained from a IIIF test engine. The IIIF is an industry standard test that uses a specially prepared gasoline engine to rate oils' high temperature oxidation properties. The samples were removed from the engine at intervals during the first 80 hours and measured in the laboratory using both the prototype sensors and a standard laboratory kinematic viscosity meter. The output of the 2-sided prototype sensor and the measured kinematic viscosity are plotted as a function of testing time in Fig. 9. The sensor correlates well with the laboratory standard test, indicating that the sensor output may provide meaningful information about the oil's viscosity. Similar results have been obtained for the 1-sided TSM prototype sensor.

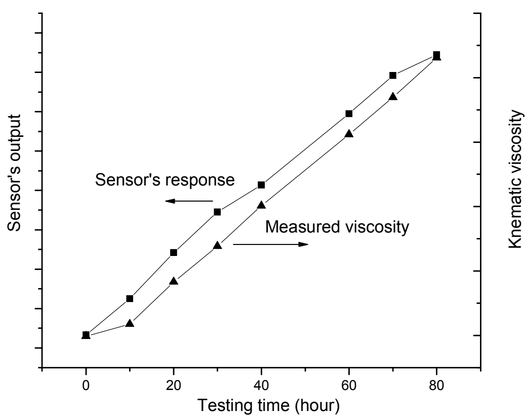


Fig.9. The response of the 2-sided TSM sensor prototype in testing IIIF drain samples

C. Oil Chemistry Effect

Large variations in engine oil formulations and oil failure modes have been found to have significant impact on certain oil quality sensors [3]. Similar behaviors were observed in the present study for the micro-acoustic wave sensor in certain situations. Fig.10 shows the test result of the 2-sided TSM prototype sensor in a series of drain samples obtained from a passenger car along with the laboratory determined $\sqrt{\rho\eta}$. It can be seen that while the sensor output correlates well with the laboratory measurement for 0, 2.5k and 13k miles samples, the correlation at 3.7k miles is poor. Similar results have also been obtained for the 1-sided TSM sensor prototype. This indicates that some factors other than the typical fluid mechanical (density and viscosity) and electrical (permittivity and conductivity) properties have affected the response of the sensor. It is not clear at this moment what mechanism caused the observed difference. However, this result shows that fluid knowledge of the engine oil is important when using the micro-acoustic wave sensor for oil viscosity measurement.

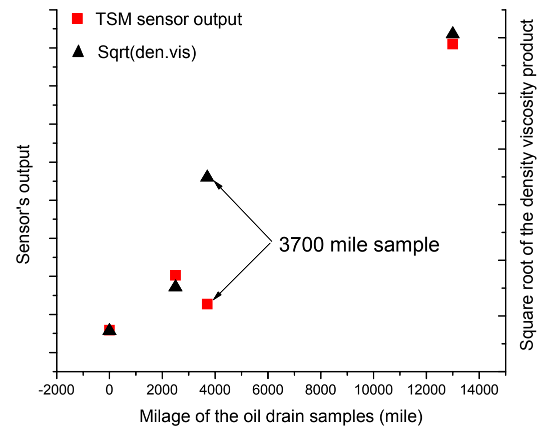


Fig.10. The response of the 2-side prototype sensor in a series of passenger car drain samples

V. Conclusions

The quartz TSM resonator with both sides in contact with fluids was tested in a variety of fluids with different mechanical and electrical properties and the measured impedance was compared with the 1-sided TSM resonator. It is found that the 2-sided TSM resonator has larger viscosity sensitivity while suffers more liquid damping than the 1-sided device. The influence of the fluid permittivity on the 2-sided device is insignificant. However, the study confirms that the 2-sided TSM resonator is not suitable for measurement in conductive fluids. Sensor prototypes have been developed for both 1- and 2-sided TSM resonators and the test results show that they may be appropriate for providing oil quality information by monitoring the viscosity change in some applications. However, the present study also found that factors other than the oil viscosity and density may have influences on the sensor response, which indicates that the fluid knowledge is important when using such sensors for engine oil applications.

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