

# Applications of Tuning Fork Resonators for Engine Oil, Fuel, Biodiesel Fuel and Urea Quality Monitoring

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## ABSTRACT

Based on a Tuning Fork flexural resonator, an innovative, miniaturized and rugged sensor that directly and simultaneously measures a fluid's dynamic viscosity, density and dielectric constant has been developed. The sensor provides a simultaneous fluid temperature measurement by incorporating a temperature sensor into the sensor assembly. The physical property measurements for viscosity, density and dielectric constant are accomplished by high performance algorithms that provide direct feedback to Engine Control Module (ECM), Urea SCR, fuel and other fluid management systems. Based on these data, real-time modification of engine or system operation can be made to optimize power, efficiency, oil drain management and emissions depending on the fluid and control system that integrates the sensor.

Single parameter sensors like electrical property sensors fail to provide sufficient information to accurately monitor fluid quality or degradation. On the contrary, the tuning fork sensor provides multi parametric analysis to enable effective fluid condition monitoring as its four measured parameters offer a 4 dimensional fluid profile based on their absolute and relative change. This technology is being applied to a variety of fluids such as engine and hydraulic oils, fuels and biofuels, transmission oils and urea.

Several key application examples are presented for discussion in this paper: assessment of fluid quality to make a smarter use of engine oil, fuel quality monitoring and unauthorized fuel identification, and finally monitoring of urea solutions quality.

## INTRODUCTION

Generally all engine and vehicle OEMs require oils and lubricants to be changed based on operating hours and or vehicle driving distance rather than actual fluid condition. This means they utilize conservative drain intervals to protect the lubricated mechanical parts. It is well known that truck fleets and corporate asset management lubrication experts utilize oil analysis laboratories to analyze grab samples of oil taken from engines and vehicles to assess the oil or lubricants condition. Many implement extended drains based on these results to reduce operating and maintenance costs associated with lubricant changes. This methodology carries an inherent risk that provides a false sense of security as a contamination event or a sudden change in oil's degradation pattern can occur immediately after sampling. Grab sample oil analysis only provides a snap shot in time of fluid condition.

Direct, in line oil and lubricant monitoring by the Fluid Property Sensor (FPS) can protect engines and machinery on a continuous basis. Until now, there was no effective means to perform real-time monitoring with sufficient capability to determine a lubricant's state with sensor price points that were acceptable to engine or vehicle OEMs. The FPS is a properly valued and optimized solution to provide OEMs with an accurate and immediate fluid condition of oils and lubricants used in engines and vehicles.

Single parameter sensors, such as conductivity sensors or acoustic viscosity sensors that only measure a single fluid parameter do not provide sufficient resolving power to reliably determine oil age and contaminant loading. For instance, if No. 2 diesel fuel were to contaminate engine oil due to piston blow-by, post-combustion fuel

injection to feed an exhaust gas after treatment system or a leaking high pressure common rail, the diesel fuel will cause the engine oil viscosity to decrease. But, the fuel contamination will cause limited to no change in dielectric constant (except if the fuel contains biodiesel) and no change in density of the oil. The FPS can easily detect this event showing a remarkable decrease in measured viscosity and no change to density and dielectric constant in the aging oil.

Thus, real-time fluid quality monitoring enables the safe extension of oil drain intervals by directly monitoring the oil degradation process and thus foreseeing when its properties are no longer appropriate to ensure proper lubrication. It supports moving from time-based to condition-based drain intervals, which is a solution to reduce expensive oil consumption while protecting the engine. An example of engine oil degradation is provided with the study of the sensor's capability to monitor three important diesel engine oil contaminants that influence oil degradation. These are water/coolant, fuel and soot. The sensor will also monitor hydraulic fluid properties over time and allow the detection of the fluid's degradation, fluid contamination and use of an incorrect fluid.

## FPS PRINCIPLE AND DESIGN

A number of sensors have been developed based on acoustic waves, thickness shear mode (TSM), or quartz crystal microbalance (QCM) resonators, see [1, 2, 3, 4]. Their applications are limited due to their enhanced sensitivity to changes in flow, pressure or contamination depending on the technology. None of them are able to directly and simultaneously measure and report the absolute viscosity, density and dielectric constant of fluids.

Flexural mechanical resonators offer a unique and powerful approach to making absolute, independent multi physical property measurements to determine the viscosity, density, dielectric constant and conductivity of fluids liquids or gases. Indeed, specific sensor elements such as tuning forks, disk or bar benders, and resonators belong to this family. The FPS sensing element is a tuning fork resonator whose impedance and frequency response are affected by the physical properties of fluids. The sensor will directly measure and report the absolute viscosity, density and dielectric constant of fluids. The sensor is calibrated with a NIST traceable oil and does not require correlation of the sensors response to laboratory methods to determine the dynamic viscosity, density and dielectric constant of fluids.

## TUNING FORK RESONATOR PRINCIPLE

The FPS tuning fork is made of piezoelectric material which is monocrystalline quartz. The tuning fork is a single structure with two tines that are metallized with

thin film electrodes that permit the crystal to resonate when energized.



**Figure 1: Tuning fork resonator.**



**Figure 2: Thin film electrodes on the tuning fork cause the tuning fork to resonate when energized.**

When the tuning fork resonator is energized and frequency scanned at its natural resonant frequency in fluids, approximately 26 kHz for oils. The change in the resonator's complex impedance at the resonant frequency is the signal used to determine the fluid's viscosity, density and dielectric constant.

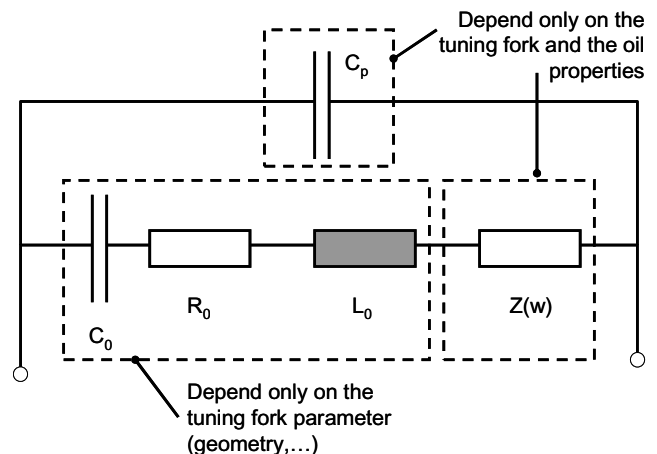


**Figure 3: Equivalent electrical circuit of a tuning fork sensor**

The complex impedance of the tuning fork resonator can be represented by an equivalent circuit (Figure 3). The

$C_0$ ,  $R_0$  and  $L_0$  respectively represent the mechanical compliance, loss and mass inertia of the tuning fork in vacuum. When placed into a fluid, an impedance  $Z(\omega)$  which models the impact of the fluid may be determined.

$$Z(\omega) = A i \omega \rho + B \sqrt{\omega \eta} \cdot (1 + i)$$

This impedance depends on the fluid properties, as  $\eta$  is the fluid's dynamic viscosity and  $\rho$  its density. The resonant frequency is  $\omega$ , while  $A$  and  $B$  are constants that depend on the tuning fork geometry and oscillation mode.

$C_p$  is the capacitance existing between the parallel electrodes which are affected by the surrounding fluid and especially by the fluid's dielectric constant  $\epsilon$ , as shown in the relationship below. The constant  $C_p(1)$  is the capacitance of the electrodes in vacuum, and  $dC_p/d\epsilon$  is the sensitivity to changes in the electrical properties of the fluid.

$$C_p(\epsilon) = C_p(1) + (\epsilon - 1) \frac{dC_p}{d\epsilon}$$

These two relationships hold a number of parameters that determined through the resonator's calibration.

The first step consists in exciting the tuning fork in air, involving  $Z(\omega)=0$ . This allows identifying  $C_0$ ,  $R_0$ ,  $L_0$  and  $C_p(1)$ . The second step consists in finding  $A$ ,  $B$ , and  $dC_p/d\epsilon$  by placing the resonator in contact with a fluid of known physical properties. The resonator response is fit to this equivalent circuit and parameters calculated with an algorithm that makes vary  $A$ ,  $B$ , and  $dC_p/d\epsilon$  independently. Now the tuning fork is ready to work in fluids of unknown viscosity, density and dielectric constant: the physical properties are obtained by fitting the sensor's response to the equivalent circuit and determining the changes in  $\eta$ ,  $\rho$  and  $\epsilon$ .

## FLUID PROPERTY SENSOR DESIGN

### Mechanical design

The FPS is a fully integrated self contained sensor assembly that integrates sensing elements and sophisticated electronics (see figure 4). Its configuration is designed to optimize the cost to performance ratio required by engine and vehicle OEMs for fluid quality and condition monitoring.

The tuning fork and a temperature sensor are mounted on electrical feed-thru protruding through a hermetic seal on the sensor housing. This permits the sensing elements to be immersed in fluids while providing total protection of the electronics contained within the FPS assembly.



**Figure 4: The Fluid Property Sensor design. View of the shroud with its openings, and thread interface.**

The entire package makes the sensor resistant to shock and vibrations while enabling high temperature fluids of up to 150°C to be monitored.

OEM standard electrical connectors enable ECM to FPS communication. The CAN signal output is compliant with universal SAE J1939 protocol [5].

### Product performances

The FPS performs real time measurement of dynamic viscosity, density, dielectric constant and temperature with a refresh rate of 30 seconds (as requested by SAE J1939 protocole). The speed of acquisition is based on a high performance algorithm. The measured physical properties are broadcast with high resolution which enables more accurate fluid characterization.

The FPS is compatible with voltage supplies from 5 to 24 Vdc with low current consumptions. Typical current consumption at 12Vdc is 40mA in steady state conditions.

## OIL DEGRADATION MEASUREMENTS

### FUEL DILUTION

Fuel dilution in engine oil is a common phenomenon in diesel engines. This situation is exacerbated with high pressure common rail, post combustion fuel injection for emission control and utilization of biodiesel fuels. The FPS will detect fuel dilution in engine oil due to these and other circumstances. The following experimental results highlight fuel dilution detection with the FPS in laboratory test environment.

### Experimental conditions

A serial dilution of 10W40 engine oil was prepared by adding commercial EN590 diesel fuel incrementally from 0 to 10 volume percent. The Fatty Acid Methyl Ester (FAME) content of the employed fuel was equal to 4.1% volume. An FPS was used to measure the viscosity, density and dielectric constant of the oil at each fuel addition. All measurements were performed at room temperature.