

Development and Testing of an Innovative Oil Condition Sensor

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ABSTRACT

In order to detect degradation of engine oil lubricant, bench testing along with a number of diesel-powered Ford trucks were instruments and tested. The purpose of the bench testing was primarily to determine performance aspects such as repeatability, hysteresis effects and so on. Vehicle testing was conducted by designing and installing a separate oil reservoir along with a circulation system which was mounted in the vicinity of the oil pan. An innovative oil sensor was directly installed on the reservoir which can measure five (5) independent oil parameters (viscosity, density, permittivity, conductance, temperature). In addition, the concept is capable of detecting the oil level continuously during normal engine operation. The sensing system consists of an ultrasonic transducer for the oil level detection as well as a Tuning Fork mechanical resonator for the oil condition measurement. Also, the sensor includes an intelligent Oil Condition Algorithm (OCA) which evaluates the incoming signals from the sensor and calculates the current oil quality considering additional information from the engine. The OCA can detect contaminants and extreme oil conditions at an early stage. The vehicles tests are conducted by utilizing a drive cycle that includes city as well as highway driving. The output generated by the sensor is processed via an on-board Data Acquisition Platform (DAP) on a real-time basis. The data collected was uploaded via telematics to a server for subsequent analysis. The results thus obtained and the

performance of the sensor will be presented in this paper.

INTRODUCTION

The importance of lubrication in today's engine cannot be overemphasized. Determination of change in critical oil degradation parameters such as viscosity, conductivity, etc. as oil ages is essential toward reliable and efficient engine operation [1]. For example, viscosity may increase as the lubricant degrades, but at the same time presence of fuel may result in masking this increase by diluting the lubricant. An on-board Hella oil condition sensor concept, which can measure dynamic viscosity, specific density, permittivity, conductance and temperature, was tested both at the bench and the vehicle levels. The purpose of the bench testing was primarily to determine performance aspects such as repeatability, hysteresis effects, and so on under a laboratory test set up; whereas vehicle testing was conducted by designing and installing a separate oil reservoir along with a lubricant circulation system to determine the robustness of the sensor under actual operating conditions. The oil condition sensor consists of a Tuning Fork mechanical resonator for the oil condition measurement. Also, the sensor includes an intelligent Oil Condition Algorithm (OCA) which evaluates the incoming signals from the sensor and calculates the current oil quality considering additional information from the engine. The software evaluates the incoming signals from the sensor and calculates the

current oil quality considering additional information from the engine. The OCA can detect contaminants and extreme oil conditions at an early stage. Oil change intervals can be optimized and the individual driving behavior can be considered in a more precise way than it is possible with existing oil condition monitoring concepts and algorithms. The vehicles tests were conducted by utilizing a drive cycle that included a mix of city and highway driving. The output generated by the sensor is processed via an on-board Data Acquisition Platform (DAP) on a real-time basis. The data collected was uploaded via telematics to a server for subsequent analysis. Additionally, periodic oil samples were collected and analyzed for validation and correlation purposes.

DESCRIPTION OF THE SENSOR

OIL CONDITION MEASUREMENT WITH TUNING FORK MECHANICAL RESONATOR

Oil condition sensors designed for automotive applications have to fulfill a lot of requirements. The main items to be considered are:

- Sensitivity of signal response level
- Short and long time stability of the signal response
- Discrimination between different oil formulations
- Simultaneous acquisition of several oil properties
- Measurement of absolute values of oil properties
- Chemical resistance
- Price

However, first of all the basic function of such an oil condition sensor is the transformation of physical and chemical parameters (such as viscosity, density, permittivity) of an unknown oil sample into electrically measurable signals.

The mechanical resonator, a so-called "Tuning-Fork", fulfills all of the above mentioned requirements. In contrast to other comparable electro-mechanical systems such as surface acoustic wave sensors (SAW), quartz crystal microbalance thickness mode sensors (QCM), thickness shear mode resonators (TSM), or membrane resonators, a Tuning Fork is capable to measure 4 independent physical parameters of a liquid e.g., dynamic viscosity, density, permittivity and electrical conductance [7, 8].

THEORY

As it was already presented in [2-7] the Tuning Fork consists of a piezo-electric material, and a mono-crystalline quartz. By electrodes placed on all sides of the surface, a periodic and elastic deformation of the body material is caused as the impact of an electric

alternating voltage. Due to the vibration an electric alternating current flows through the electrodes. The ratio between stimulating alternating voltage and resulting alternating current is the electric impedance of this electro-mechanical system. It can be directly measured as a function of the stimulating frequency, the elastic material properties, the hydrodynamic properties of the sensor surface, and the physical properties of the ambient medium.

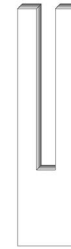


Figure 1: Basic geometry of a Tuning Fork resonator

Near its resonant frequency, which is in the lower kHz range, the amplitude of the volume oscillation of the Tuning Fork is in the range of some 100 nm. However, due to the specific balanced design the system is very robust against outer perturbations such as mechanical vibrations, shocks on the sensor mounting, or acoustic noise.

The mechanical, electrical and hydrodynamic impacts of the ambient medium to the Tuning Fork resonator are modeled by an equivalent electrical circuit for the measured complex impedance as described in [7].

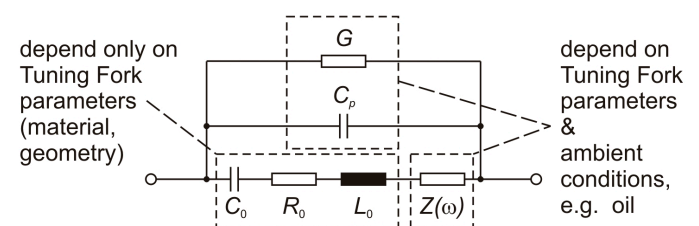


Figure 2: Equivalent electrical circuit of a Tuning Fork sensor

Depending on only the material and the geometry the parameters C_0 , R_0 and L_0 represent the mechanical compliance, loss, and mass inertia of the resonator in vacuum. The electrical stray field of the electrodes determines the value C_p and the electrical conductance G resulting in the permittivity ϵ and the conductance σ of an ambient medium. The mechanical and hydrodynamic influence of an ambient medium like oil is modeled with an additional term $Z(\omega)$. For the Tuning-Fork resonator it is given by the following equation:

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

$$C_p(\varepsilon) = (\varepsilon - 1) \cdot \frac{\partial C_p}{\partial \varepsilon} + C_p(1) \quad (2)$$

$$G(\sigma) = \sigma \cdot \frac{\partial G}{\partial \sigma} \quad (3)$$

In equation (1) ω is the stimulating frequency of the Tuning Fork, η is the dynamic viscosity and ρ is the specific density of the ambient medium. A and B are specific model parameters that have to be determined by a calibration of the system in an well-known calibration liquid.

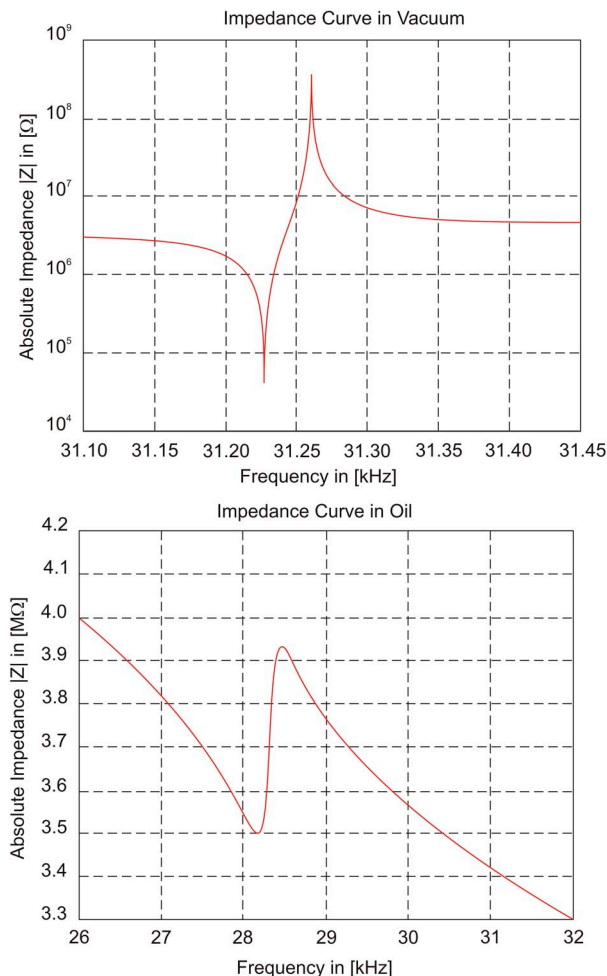


Figure 3: Influence of engine oil to the absolute impedance of a Tuning Fork resonator

A specific “open cavity molding” technology (see [9]) produces a clearance around the Tuning Fork that allows a free, all-sided contact of the sensor element to the measurement medium. A high temperature stable and chemical resistant nano-coating on the Tuning Fork prevents the deposition of oil residual particles such as soot and guarantees a long-term stability of the quartz mechanical resonator

For a high-precision, fast and nearby temperature detection a silicon-based sensor circuitry on the ASIC measures the oil temperature close to the position of the resonator. The admittance computed as the quotient of the measured alternating electrical current through the Tuning Fork electrodes and the stimulating sinusoidal alternating voltage is provided as a digital signal at the data interface together with the stimulating frequency and oil temperature.

Using the mathematical model of the Tuning Fork as described above an external microcontroller calculates the dynamic viscosity, density, permittivity, and conductance via application of a least mean square fit algorithm.

A-SAMPLE CONFIGURATION

The Tuning Fork multi-chip module as in figure 4 was assembled on a mechanical flange. To damp the oil flow around the sensor and prevent external turbulences, a small plastic housing has been mounted on top of the mechanical flange. The damping cap has a small oil inlet hole on the bottom side and an air intake on the top side. This setup corresponds to the Packaged Ultrasonic Oil Level Sensor ‘PULS’ produced by the company HELLA.

For a preconditioning of the digital signal transmitted from the Tuning Fork multi-chip module an external micro-controller was connected to the sensor. It acted concurrently as a signal converter to a PC-based evaluation software (see Figure 4). Alternatively, a customized data interface can be provided to connect the sensor system directly to a standard automotive bus like CAN or LIN (Figure 5). For offline measurements of single oil samples on a laboratory workbench a small metallic test vessel was assembled on the sensor flange (Figure 6).



Figure 4: Tuning Fork multi-chip module (left), mechanical flange without Tuning Fork multi-chip module and damping cap (middle), full A-sample with damping cap (right)