Micro-sensors for automotive liquid properties monitoring

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0. Summary

Because of upcoming new emission regulations like Euro 6 or EPA10 the fuel efficiency, emissions and lifetime of modern combustion engines need to be increased by a sophisticated engine management. Additionally, an increased fraction of fuel admixtures of bio-ethanol or bio-diesel together with new technologies like particle filters in the exhaust gas after treatment components of diesel engines become more and more important.
To cover all of these new requirements a lot of parameters have to be considered. Sensor systems currently available on the market are not sufficient because either they are too big, too slow and/or too expensive for an automotive integration.
Using examples of an oil level & quality sensor and an ethanol content & pressure sensor it will be demonstrated how the integration of different functionalities in small micro-sensors for automotive applications can be realized.

1. 'PULS+C' – A combined oil level & condition sensor

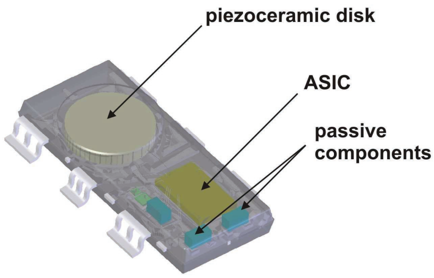
Introduction

Essential for an optimized service interval determination, which is specifically adapted to the engine and the current driving situation, is a consideration of the actual oil condition. Hereby, an oil change is predicted more precisely than is possible with conventional indirect algorithms. Continuous oil quality monitoring with sensors directly integrated in the oil circulation is the one and only method to react on critical conditions.
With this focus Hella has developed sensors for the measurement of oil level, oil condition, and oil temperature based on the same multi-chip module technology. By means of comprehensive studies on samples of fresh and used oils, an intelligent Oil Condition Algorithm (OCA) was developed, which is capable of appraising the current oil quality. The core OCA is based on a mathematical classification algorithm which makes use of all data that is provided by the integrated oil sensors. The functionality and reliability of the OCA will be adapted to engine or engine platforms by tests on engine benches and car fleets together with the OEM.
Together with the OCA, the combi-sensor 'PULS+C' (Packaged Ultrasonic Level Sensor + Condition) is an early warning system which enables optimal usage of the engine oil, an increase of the lifetime of the engine, a reduction of exhausts and, last but not least, makes the oil dipstick a redundant component.

Sensor Design

The combination sensor is designed to enclose two separate multi-chip modules into a single mechanical flange. One module is for oil level and oil temperature sensing. The other measures the oil quality. Both sensor elements are packaged together with an ASIC and additional passive components into a standard IC package according to JEDEC SOIC-28. For the measurement of the oil level we use our series sensor PULS (Packaged Ultrasonic Level Sesnor). It is designed as a cylindrical TSM resonator, based on a ceramic composite material. By its polarization direction the piezoelectric resonator works in a thickness shear mode and decouples the ultrasound via the adjoined surfaces. The transducer is completely encapsulated the package using an assembly process, which is already established and qualified in IC technology. The piezoceramic disk as well as its contact metallizations are thereby ideally protected against oil influence. This could be proven by extensive qualification tests in oil and other aggressive media, such as gasoline, diesel fuel, biodiesel, and glycol.
The oil quality measurement is performed by our Tuning Fork Sensor. The Tuning Fork as the basis element of the oil condition sensor consists of a piezo-electric material, a mono-crystalline quartz. By electrodes on all sides of the surface, a periodic and elastic deformation of the body material is caused by the impact of an electric alternating voltage. This vibration produces an electric alternating current that flows through the electrodes. The electric impedance considered as the ratio between stimulating alternating voltage and resulting alternating current is a function depending on stimulating frequency, the elastic material properties, the hydrodynamic properties of the sensor surface, and the physical properties

of the ambient medium. For a measurement of the mechanical damping and mass loading of the Tuning Fork vibrating in a fluid (such as e.g. oil), this resonator is operated in the range of its resonant frequency. Due to the chosen design, this frequency is located for the presented sensor in the lower kHz range. Despite the volume oscillation of the Tuning Fork, which has an amplitude of some 100 nm, it is very robust against outer perturbations such as mechanical vibrations, shocks on the sensor mounting, or acoustic noise due to the specific balanced design.



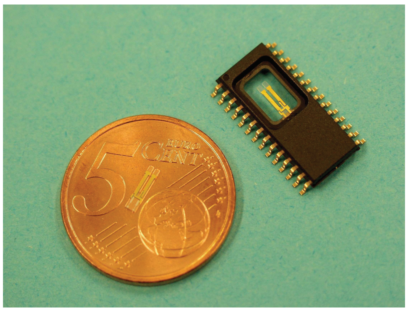


Figure 1: Multi-chip modules (MCM): Left: Packaged Ultrasonic Level Sensor (PULS); Right: Tuning Fork multi-chip module with a 5 Euro-Cent coin

For the analysis of changes in the resonant curve we employ an electromechanical model. The complex impedance of flexural resonators (such as of a Tuning-Fork sensor) can be modeled with an equivalent electrical circuit. The model formulas contain the variables dynamic viscosity η, the specific density ρ, the permittivity ε and the electrical conductance σ of the ambient medium. By means of a non-linear optimization algorithm these parameters are computed and give direct information about the physical condition parameters. There is also a silicon based temperature sensor integrated in the ASIC that allows for a fast, nearby, and precise measurement of the oil temperature. Since the viscosity of the oil depends highly nonlinear on the temperature, it is necessary to measure the temperature close to the position of the resonator. Therefore, the position of the temperature sensor represents an essential quality factor.

The control priciple of the PULS is based on an ASIC that was developed for the application. It stimulates the ultrasonic transducer with its resonant frequency. For that a short pulse of frequency 2 MHz is generated and coded by a phase change. The ultrasound wave reflected by the oil surface is evaluated by means of a correlation algorithm, and the actual signal propagation delay is measured. An 8-bit microcontroller integrated on the ASIC calculates the oil level and transfers this result as a digital signal to the external ECU via a 1-wire data interface. As transfer protocols, PWM, LIN, or SENT can optionally be used. The oil temperature (measured by a silicon-based temperature sensor available on the ASIC, or an external resistive sensor element) can also be transmitted to the ECU.

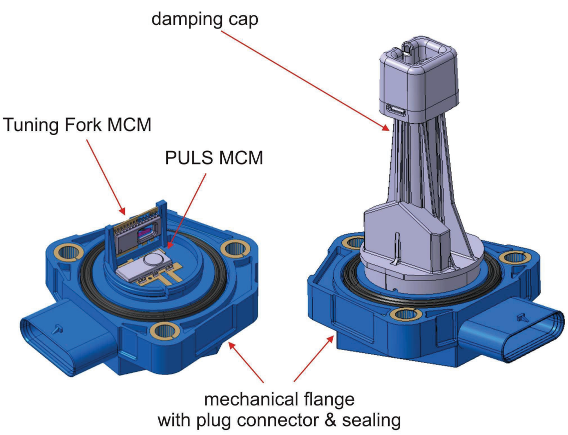


Figure 2: Product example of oil level sensor PULS with separate temperature sensor (left: top view of sensor without damping cap)

A damping cap mounted above the sensor element on the oil-tight flange contributes to a calming effect of the oil. In normal operation when the engine is running, the oil level to be measured is within the damping cap. For an overfilling, as well as for a static case (when the engine is stopped), the oil level can rise above the damping cap. By a directed material selection and a specific design, this cap was optimized such that an undamped transmission of the ultrasonic wave is ensured relative to the outside of

the cap. Hereby, the measurement of the oil level is possible before the engine is started. This functionality turns the sensor into an ‘electronic dipstick’.
The maximum measurement range, or the maximum oil level that can be measured is no longer determined by the outline of the sensor, but by the acoustic damping of the ultrasound over the entire distance. For a desired signal of 2 MHz the damping coefficient in oil is in the range of 1 to 5 dB/cm. Using a 100 dB signal amplification on the ASIC, there are distances up to 100 cm or oil levels up to 50 cm, resp., are theoretically measurable. With regard to an optimized RAM and ROM memory usage on the ASIC the correlation measuring method in the oil level sensor PULS was limited to a maximum oil level of 30 cm.

Oil Condition Algorithm

For the computation of engine maintenance intervals the examination of the actual existing oil condition is the crucial point for an algorithm that is adapted to an engine and considerates different driving styles.
The Oil Condition Algorithm (OCA) computes the oil condition from parameters that are directly measured in the oil (dynamic viscosity, specific density, permittivity, conductance, oil level, and oil temperature). In contrast to common techniques it is now possible to confirm recommended oil maintenance intervals, or to provide them with higher accuracy. The main advantage of this in-situ analysis is the optimal use of the oil life. Moreover, the oil condition algorithm provides an early stage warning system that allows for the prevention of engine damages.

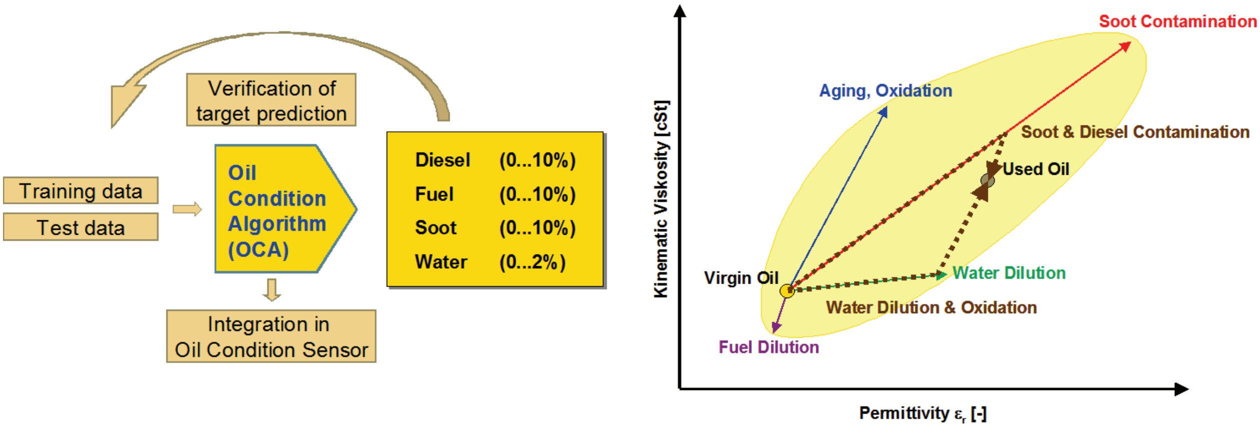


Figure 3: Left: Training and Verification of the oil condition algorithm (OCA); Right: Ambiguous oil aging due to oxidation as well as contaminations with soot, fuel, or water

The principal target of the development of the Oil Condition Algorithm is the design of a classification routine that efficiently maps a set of input oil parameters to a previously defined oil quality label. In this way, important oil quality properties such as soot content, water, or diesel dilution can be detected.

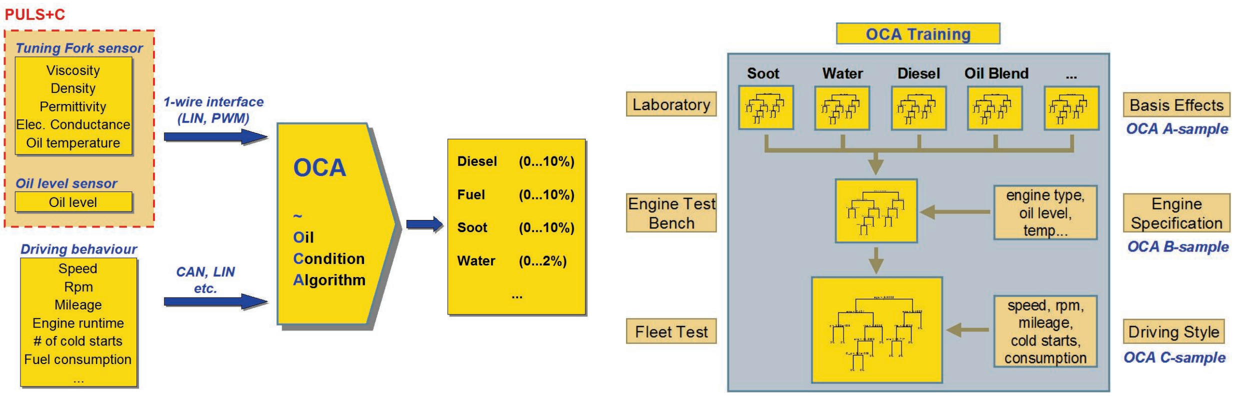


Figure 4: Left: Principle of the OCA; Right: Roadmap for the expansion of the training data set to adapt the oil condition algorithm to different oil grades, engine types, and driving styles

One great advantage of the Oil Condition Algorithm is the multi-dimensional analysis of the oil parameters where they are nonlinearly combined to predict the oil condition. In this way, the connection between oil parameters and oil quality is described sufficiently and a reliable prediction is ensured.

2. Fuel sensor for absolute fuel pressure, temperature and ethanol content

Ethanol content

By a voluntary commitment of the US based car manufacturers half of the new cars fleet from model year 2012 onwards should be capable to run on flex-fuel (variable mixtures from regular fuel and ethanol). The different evaporation and combustion properties of ethanol do demand an adaption of map based engine control. The hardware sensor solution described in this paper offers advantages in regard to fuel efficiency and exhaust gas behaviour - especially at engine start and during cold-start phase - in comparison to a software based solution ("virtual sensor"). The virtual sensor is a calculation intensive task and relies on data provided by the lambda sond, which is difficult because of the already existing calculation load due to OBD II requirements. The cold start capability is improved, too.

Absolute fuel pressure

In modern cars with direct injection petrol engines there is only one supply line from the fuel tank to the injection rail. An on-demand fuel supply by control of the electrical fuel pump is therefor mandatory. This requires an absolute fuel pressure sensor which is mounted either close to the injection system or close to the fuel pump inside the fuel supply module itself. The absolute fuel pressure sensor at the low pressure side is needed to ensure a buble free fuel supply to the high pressure pump under all engine load conditions. Otherwise, the high pressure pump might be damaged by imploding fuel bubles.
The combination of the afore described two basic functions at one mounting location offer synergy potentials to the customer.

Sensor design

The combination sensor is based on the concept [1] of a novel oil pressure sensor and takes over parts from the used Multi-Chip-Module (MCM) to measure absolute pressure and temperatures. In the prototype, the MCM is mounted on a printed cicuit board, on which also the capacitive measurement configuration - realized as four electrodes - and the accociated read-out electronics are placed.

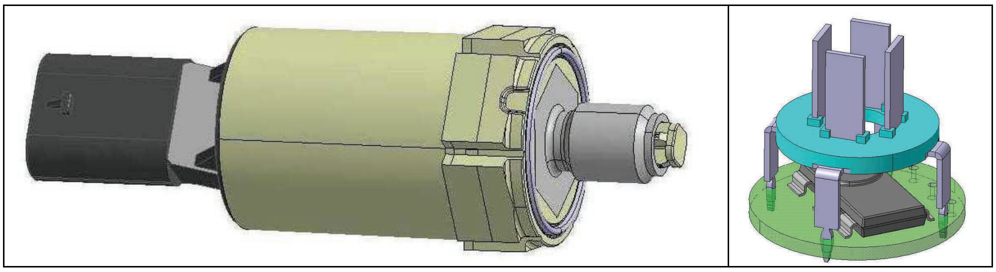


Figure 4: Combination sensor for fuel pressure and ethanol concentration as all-plastic, two part laser-welded solution, thread-flange with metal insert and fuel resistant sealing (left)**,** electrode configuration on printed cicuit board for impedance spectroscopy of the fuel mixture, incl. Multi-Chip-Module for pressure and temperature measurement (right, located underneath the electrode configuration)

Fluidic design

In this case the sensor is no in-line solution in comparison to existing sensor solutions for measurement of ethanol content in fuel [2]. It is a by-pass screw-in solution comparable to the existing fuel pressure sensors for liquid fuel pressure already in the field. To achive the required low response time <1s across the high dynamic range of volume flow rate − 0,8l/h in idle mode, up to 400l/h at full throttle in a big V8 engine − a defined mixture and turn-over rate between the electrodes must be ensured.
By performing CFD analysis the minimum srew-in depth was determined at the same time ensuring that the specified maximum pressure drop of 3kPa is not exceeded. An easy to manufacture fluidic adapter concept was developed together with a manufacturer of fuel supply lines. The adapter can be integrated into existing fuel supply lines with minimum effort.

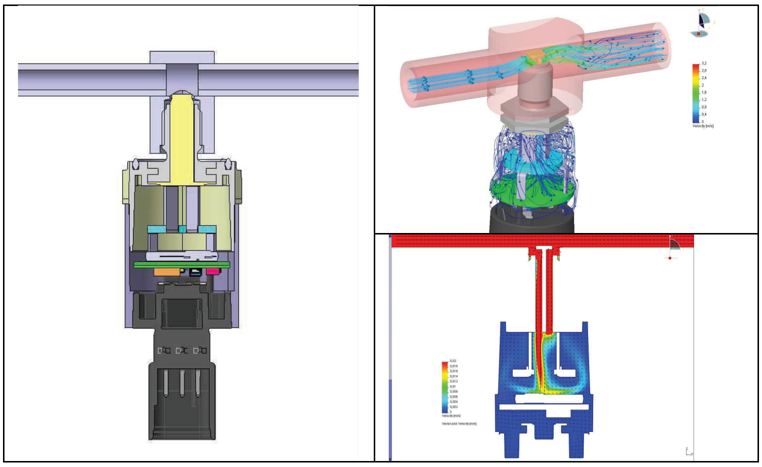


Figure 5: Cross-section of the sensor, screwed in a 3/8'' fuel supply line (left), 3D CFD (Computational Fluid Dynamics) simulation model of volume flow through the sensor (top right), cross-section for volume flow rate of V' = 114l/h (right bottom).

Measurement of fuel pressure and temperature

The fuel pressure is measured by a fully temperature compensated piezo-resistive MEMS pressure sensor element, which is designed for use inside aggressive media. The pressure sensor element also contains an integrated diode for measuring the fuel temperature directly at the location of pressure measurement. The temperature reading is primarily used for compensation of the temperature dependency of the piezoresistive sensor element. Additionally, the true fuel temperature can also be output via e.g. the digital single-edge nibble transmission (SENT) protocol. The pressure sensor element is mounted together with a dedicated application specific integrated circuit (ASIC) and passive protection and output filtering circuitry on a standard integrated circuit (IC) lead-frame and molded with thermoset material. During the molding of the MCM the pressure sensor access hole is kept free of mold compound to allow the media to access the backside of the pressure sensor element's membrane.

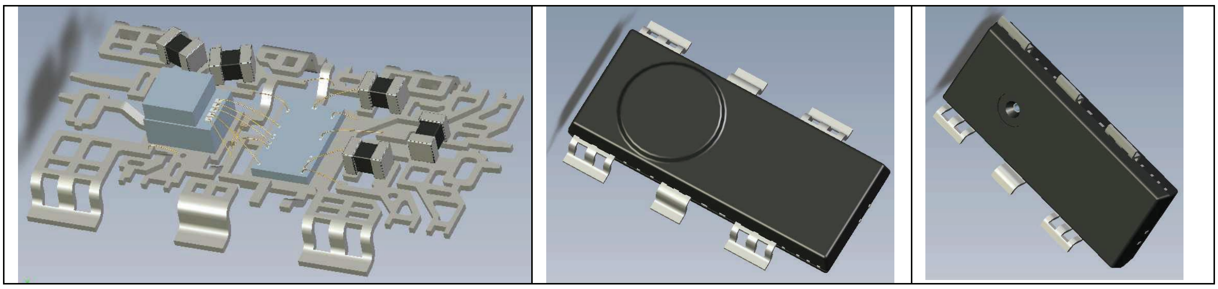


Figure 6: MCM for pressure and temperature measurement before (left) and after thermoset over-molding

Measurement of ethanol content

The mixture rate of the two fluids ethanol and regular fuel is based on the large difference of dielectric constant:

(1) Ethanol (chemical formula: C_2H_6O) is a polar molecule with ε_r ~ 24,3 at 25°C
(2) Regular fuel is unpolar with ε_r ~ 2,2 at 25°C

The resulting dielectric constant of the mixture can be detected by a capacitive measurement configuration using an IC for impedance measurement in a frequency range from 1000Hz up to 100kHz. The fuel conductivity (e.g. by water content, uptake of salt and other ions) is also influencing the resulting complex impedance. The resulting mixture ratio is calculated with a small local microcontroller from the impedance spectra and the measured temperatures by an algorithm based on descison trees and a local regression. The final value is than output directly to the tank or engine ECU via a digital interface togeher with fuel pressure and temperature reading.

Results

After the design of experiments (DoE) a set of raw data measurements (impedance spectra) at different temperatures and ethanol concentrations was perfomed at a specialized lab to optimize and parameterize the algorithm.

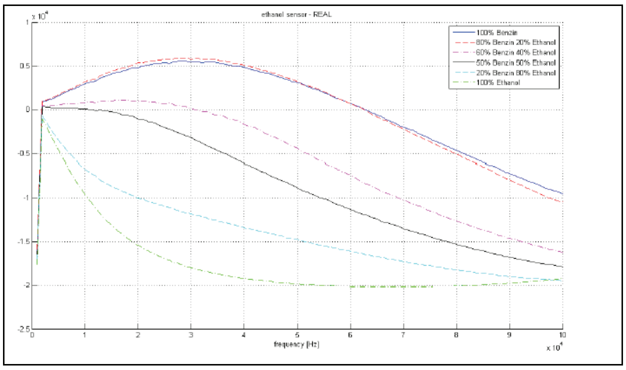


Figure 7: Comparison of real part of impedance for 0, 20, 40, 50 and 100% ethanol in fuel

Prototypes of the new sensors where initialy tested by test drives together with a customer.

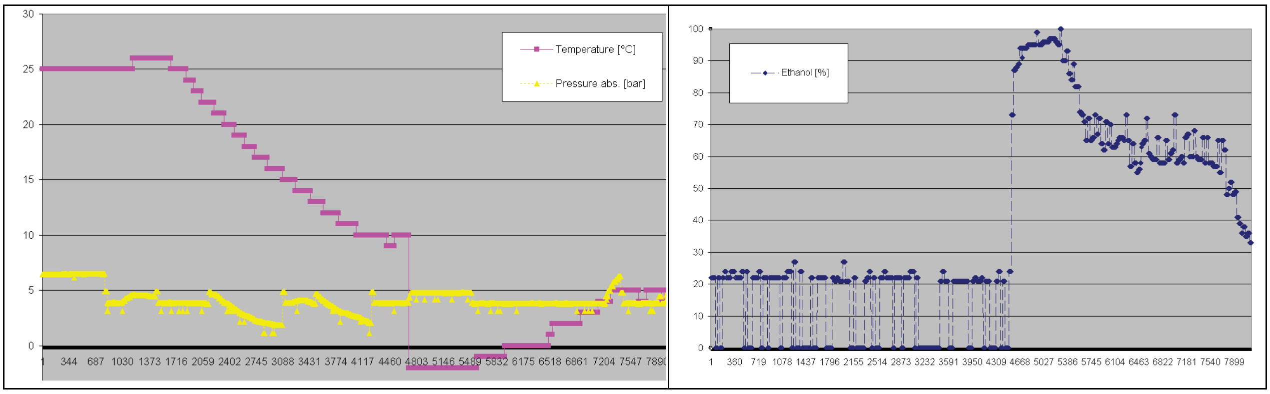


Figure 8: Test drive with fuel temperature and pressure (left), ethanol content after consecutive re-fill procedure with E0, E85, E50 and E20 (number indicating percentage of ethanol).

Summary

The combi-sensor for oil level and oil condition, together with the oil condition algorithm is able to prevent damage at an early stage, and to detect foreign substances. In contrast to common oil management concepts and algorithms, it is now possible, via the integration of the entire system of hardware and software in the oil management of vehicles, to adapt maintenance intervals and oil changes more specifically and precisely to the corresponding vehicle and driving styles.

A new combination sensor for fuel pressure, -temperature and ethanol content was developed and first prototypes were successfully tested for functionality. The universal fuel sensor can replace single fuel pressure, fuel temperature and single ethanol sensors and can optionally be equipped with ethanol function. Additional mounting spaces like direct integation into the tank conveyor module are studied at the moment.

References

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