Sensors and Interface Electronics for Oil Condition Monitoring

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In this contribution, we discuss the suitability of physical sensors for oil condition monitoring. For the oil's viscosity, microacoustic sensors can be utilized. Standard readout concepts for microacoustic sensors are currently based on either bulky and expensive measurement equipment or electronic oscillator circuits. These oscillators malfunction in case of higher viscosities due to the associated higher device damping. Thus, we present an alternative measurement approach, which can be implemented in a compact fashion with cost-effective standard components.

Introduction

The monitoring of oil and oil-based liquids (including emulsions) is an important task in a number of application areas ranging from the food industry to automotive applications. In the latter field, there has recently been increased interest in monitoring the condition of lubricants facilitating proper engine operation. Monitoring the engine oil condition at first instance allows the implementation of increased oil drain intervals. Moreover, it provides increased insight into the actual state of the engine, which enables the detection of possibly approaching engine failures but also the monitoring of the performance of engine oils of varying quality. Similar considerations hold for other applications where oils are used as lubricants.

An Example – Sensors for Automotive Engine Oil

Flexible oil drain intervals for engine oil are currently commonly determined by continuously monitoring characteristic engine and driving parameters (such as, e.g., driven distance, speed, and oil temperature) [1]. The proper oil drain interval is then indirectly estimated by means of corresponding algorithms processing these parameters. However, ideally the evaluation of the oil condition should solely be based on parameters measured *directly* in the oil itself. Considering the procedures that are utilized in "off-board" oil condition evaluation by experienced, specialized laboratories, one finds that an oil condition evaluation based on physical parameters would require a large array of sensors, which often cannot be integrated in an on-board sensor system or do not offer the desired long-term stability. Alternatively, a multifunctional sensor for the oil's viscosity, permittivity, temperature, and oil level can be used [2]. These parameters are to be processed by algorithms, which combine the ease of the indirect approach and the advantages of directly considering physical oil parameters. The measured viscosity and permittivity are the primary quantities supporting the oil condition evaluation. The temperature measurement is necessary, as the measured parameters are temperature-dependent. This approach represents the implementation of a so-called *physical chemosensor* [3] where *chemical* liquid properties ("oil quality" in this case) are sensed solely by means of *physical* sensors. In contrast to *chemical sensors*, these sensors do not use chemical interfaces, which feature a number of disadvantages like ageing, drift and lacking reproducibility.

The determination of two indicator quantities for the oil quality allows the discrimination of different oil strain scenarios. As an example, Fig. 1 shows measured values for a "normally" strained oil, which has been sampled from an engine after 19,000 km of test driving, and the same oil type which has been used during cold start tests (15 starts @ -15°C) which leads to fuel dilution of the oil [4]. These oils and the corresponding new oil each correspond to a point in the permittivity–viscosity plot in Fig. 1. It can be seen that, as expected, the oil with fuel dilution shows a decrease in viscosity (fuel features a lower viscosity than engine oil) whereas the "normally" aged oil leads to an increase in viscosity (mainly due to the oxidation of the oil). However, the permittivity signal only shows a major change for the "normally" aged oil, because fuel shows a similar permittivity as engine oil. This example illustrates the increased insight gained by monitoring two parameters compared to monitoring a single quantity.

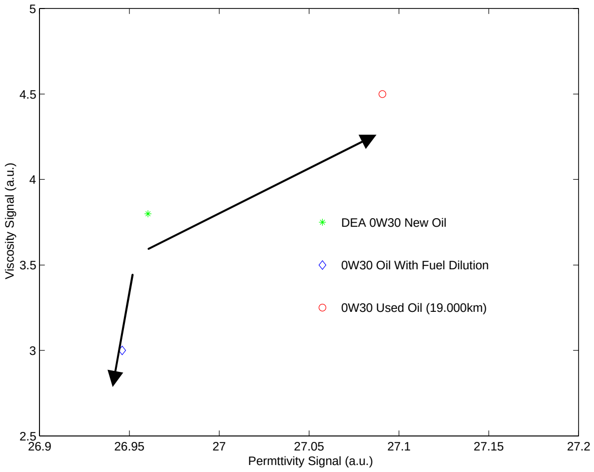

Fig. 1: Simultaneous measurement of viscosity η and permittivity ε @ 25°C [4].

Microacoustic Viscosity Sensors

While the implementation of permittivity sensors is straightforward (this can be, e.g., done by using a coaxial capacitor immersed in the oil to be measured [5], [6]), the viscosity measurement is more sophisticated. In order to avoid macroscopically moving parts as they would be used in conventional viscometers, so-called microacoustic viscosity sensors can be used. These devices excite special shear-polarized mechanical (or acoustic) oscillations in a piezoelectric crystal. Due to the coupling with an adjacent viscous liquid, the electrical device characteristics change according to the viscosity of the liquid. Examples for shear polarized microacoustic wave-types are BAW shear resonators (also called transverse shear mode or TSM resonators), leaky SAWs showing a dominant shear polarization, shear polarized acoustic plate modes, and Love waves (see [7] for an overview). Figure 2 shows the principle of a Love wave delay line which can be used as sensor. The device consists of a piezoelectric substrate supporting shear-polarized modes, interdigital transducers for the excitation and detection of the wave, and an isotropic guiding layer [7].

Liquid loading of a device performing a shear oscillation leads to an entrainment of a thin liquid film with exponential decay of the entrained shear movement (see Fig. 2, [7]), where the decay length δ is given by $\delta = \sqrt{2\eta / \rho\omega}$. Here η and ρ denote the dynamic viscosity and the mass density of the liquid, and ω stands for the angular frequency of the oscillation. The entrainment leads to (i) a mass-loading of the device causing a change in resonance frequency (in case of a resonator) or a change in phase velocity (in case of a delay line as described above), and (ii) a damping of the oscillation or the wave. Both effects are to first order proportional to $\sqrt{\omega\eta\rho}$ and thus a sensor for the viscosity-density product can be realized. For non-smooth surfaces, parts of the liquid can be "trapped" leading to an additional pure mass-loading effect, which corresponds to the density of the liquid. Thus using two sensors, one with a smooth and one with a corrugated surface, makes it possible to distinguish between the effects of viscosity and density [7]. However, in many applications, changes in viscosity outweigh changes in density such that sensors with smooth surfaces represent efficient monitoring devices for the viscosity.

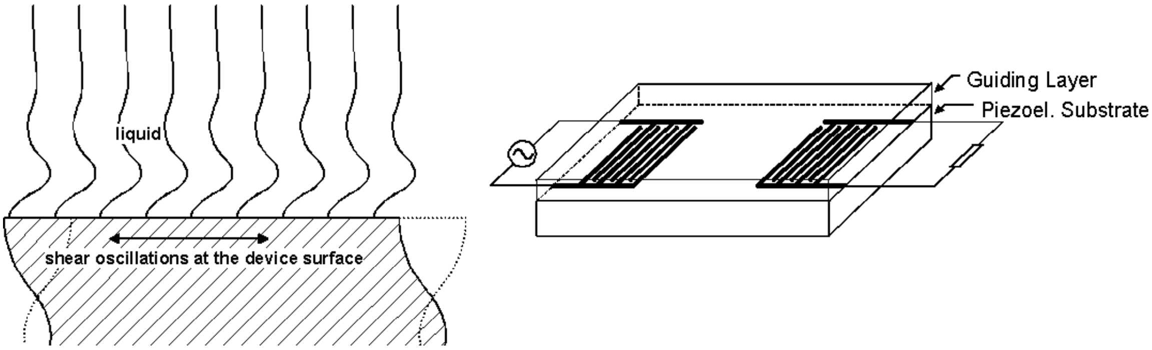

Fig. 2: Entrainment of a liquid with a shear oscillation (left) and principle of a Love wave delay line (right).

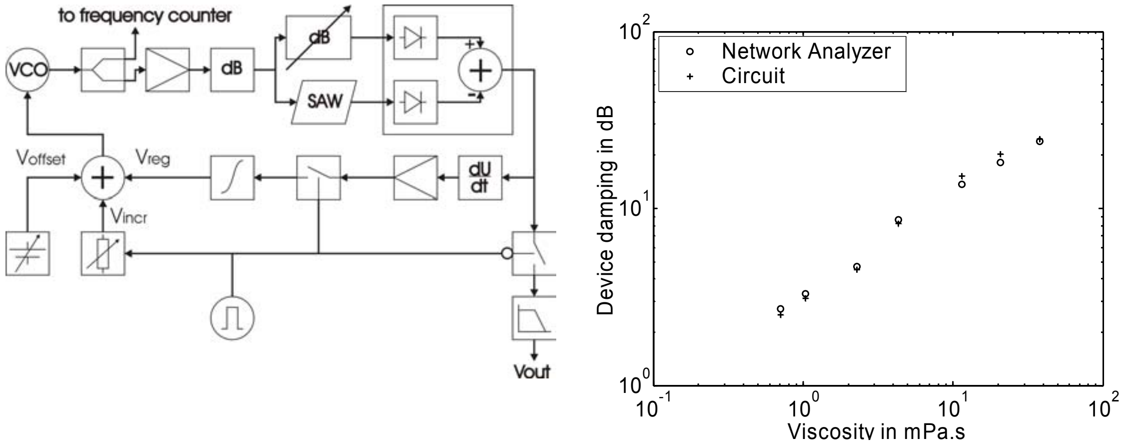

Fig. 3: Block diagram of the circuit (left) and measurement results (right).

Interface Electronics for Love Wave Viscosity Sensors

Standard readout concepts for microacoustic sensors are currently based on either bulky or expensive measurement equipment or electronic oscillator circuits using the sensor (resonator or delay line) as frequency determining element. These oscillators malfunction in case of higher viscosities due to the associated higher device damping. Hence we developed a dedicated circuit which automatically measures the damping of the delay line at its resonance frequency. This is achieved by implementing a control loop, which detects the slope of the damping-frequency characteristics by means of feeding the delay line with a frequency modulated VCO signal at its input and detecting the amplitude at the output. At the center frequency f_0 this slope and thus also the amplitude changes due to the frequency modulation vanish, which is utilized to tune the center frequency of the VCO to f_0 by means of a control loop. Figure 3 shows the block diagram of the circuit and measurement results showing the correlation of the device damping (obtained from the circuit and a network analyzer measurement as reference), with the viscosity as obtained by using a rotational viscometer. More details can be found in [8].

Summary

For many applications, the monitoring of oil-based liquids is of crucial importance. In this contribution, we reviewed recent developments in the field of physical chemosensors for this purpose. Particularly we discussed a novel approach for the readout of Love-wave viscosity sensors, which avoids the problems occurring with commonly used oscillator circuits.

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References

[1] R. Thom, K. Kollmann, W. Warnecke, M. Frend: “Extended Oil Drain Intervals: Conservation of Resources or Reduction of Engine Life”, SAE paper no. 951035, 1995.

[2] B. Jakoby, M. Buskies, M. Scherer, S. Henzler, H. Eisenschmid, O. Schatz: “A novel multifunctional oil condition sensor”, in Advanced Microsystems for Automotive Applications 2001 (S. Krueger and W. Gessner, eds.), p. 157–165, Berlin Heidelberg New York: Springer, 2001.

[3] M.J. Vellekoop: ”The emerging of physical chemosensors and biosensors”, Proc. Transducers ´01, Munich, Germany, p. 770-775, June 2001.

[4] B. Jakoby, H. Eisenschmid, and F. Herrmann: “The potential of microacoustic SAW- and BAW-based sensors for automotive applications - a review,” IEEE Sensors Journal, vol. 2, pp. 443–452, Oct. 2002.

[5] E. Irion, K. Land, T. Gürtler, M. Klein: Oil-Quality Prediction and Oil-Level Detection with the TEMIC QLT-Sensor Leads to Variable Maintenance Intervals, SAE Technical Paper Series No. 970847, 1997.

[6] B. Jakoby and M. Vellekoop: “Monitoring water-in-oil emulsions using physical sensors,” in Proc. 16th European Conference on Solid-State Transducers (Eurosensors XVI), Prague, Czech Republic, pp. 53–56, 2002.

[7] F. Herrmann, B. Jakoby, J. Rabe, and S. Büttgenbach: “Microacoustic sensors for liquid monitoring,” in *Sensors Update* (H. Baltes, J. Hesse, and J. Korvink, eds.), vol. 9, pp. 105–160, Weinheim: Wiley VCH, 2001.

[8] J. Bastemeijer, B. Jakoby, A. Bossche, M. Vellekoop: “A Novel Read-Out System for Microacoustic Viscosity Sensors”, Proc. IEEE Ultrasonics Symposium, Oct. 2002, Munich, Germany