# Innovative sensor technology revolutionizes lubrication system analysis in transmissions

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**Abstract.** With increasing requirements for transmissions in terms of rotational speed and geometrical constraints, the topic of lubrication gains in importance. In the future, more accurate and sophisticated lubrication system analysis methods will be needed to ensure functionality in series applications. Therefore, it is necessary to reconsider current testing methods like tilt tests based on visual inspections with transparent housings and pursue new and innovative approaches for test and verification as well as for condition monitoring. One of those approaches was developed at the Graz University of Technology and comes in the form of a unique fluid sensor. The innovative sensor was designed for the quantification of multiphase flows and is ideal for analyzing the lubrication in transmissions. By integrating several measurement principles into one miniaturized sensor, the flow and the temperature of the oil are measured. Furthermore, the sensor is able to detect gas bubbles and oil splashes. The combination of the obtained measurement data from several of these innovative sensors at different positions is used to determine the exact lubrication condition dependent on rotational speed, tilt angle and oil temperature.  Different sensor designs like a sensor probe or an adhesive sensor foil allow measurements at individual test points inside of the transmission. Together with the objective of implementing a wireless data transfer, this sensor application provides a new way of analyzing lubrication conditions.

**Keywords:** lubrication transmission sysem analysis, lubrication sensor, multiphase flow sensor.

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# 1 Introduction

The increasing power density and speed of electrified of powertrains brings up many new challenges for the field of lubrication. Especially for the lubrication system analysis, current test methods are facing the limit of their capabilities and need to be reconsidered for coming development projects. Overall, the fundamental knowledge about the behaviour of the lubrication becomes more and more a key factor in understanding the system from a tribological point of view and in increasing efficiency. Traditional testing methods are often not accurate enough for quantifying the oil supply of specific machine components inside of the powertrain. Therefore, the Institute of Machine Components and Methods of Development at the Graz University of Technology set up a new standard for verifying the multiphase lubricant flow inside of a transmission with a patented sensor system. The innovative sensor technology combines two measurement principles at the size of a *match stick*, which allows new insights into multiphase flow analysis. The implemented functions of the sensor are gas and liquid detection, as well as a measurement of the flow velocity and the temperature of the fluid. The compact size of the sensor allows minimal invasive flow metering inside of a transmission.

The purpose of this paper is to give new insights into lubrication system analysis and to explore new technologies for that purpose. First, the targets of the research are explained, followed by an introduction of the measurement principle. Furthermore, a pilot project at the AVL-TU Graz Transmission Center is used to explain the technology, the application, and the benefits of its usage. In addition, a new procedure for lubrication system analysis implemented with this technology is explained and compared to traditional methods.

# 2 Targets

The Institute of Machine Components and Methods of Development at the Graz University of Technology operates a Transmission Center (TC) in cooperation with AVL List GmbH, where basic research on powertrains is performed. One research focus of powertrain development is tribology, especially the lubrication system analysis of gearboxes. A particular type of test cell, the dynamic tilt rig is used to evaluate the lubrication condition of the transmission depending on the rotational speed and tilt angle. The tilt angle represents the acceleration forces caused by lateral acceleration, longitudinal acceleration, or climbing conditions that act on the transmission at real drive operation and therefore cause dynamic lubricant flow.

Additionaly, several methods are used to validate the oil distribution. Most often, these methods include visual analyses with camera systems through transparent housings. However, due to high-speed tests and complex structures of the gearbox, usually, there exists no optical path to the analysis point of interest. In figure 1, a concrete example of such a visual oil supply analysis of a bearing inside of the transmission is illustrated.

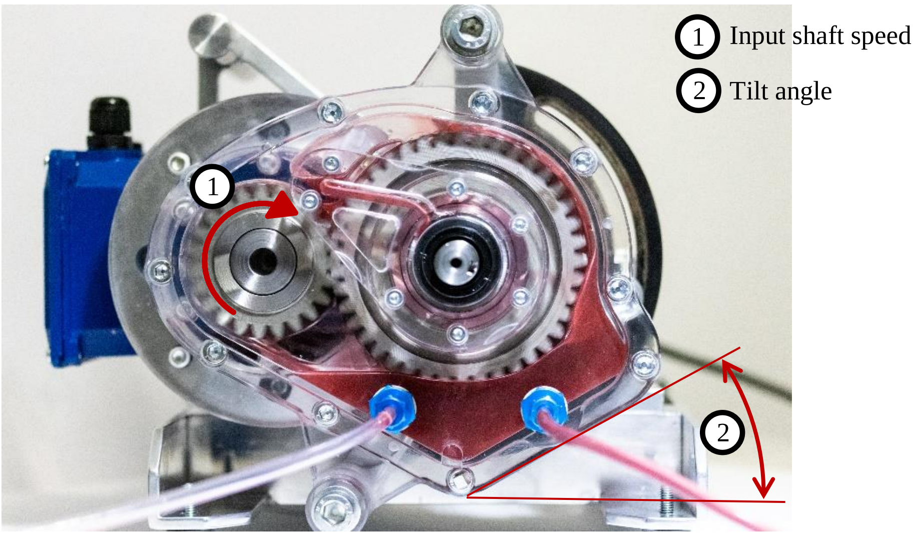


**Fig. 1.** Visual inspection of oil distribution inside a transmission through a transparent housing.

A test matrix defines a set of a specified tilt angles and the input shaft speeds of the gearbox, and is the starting point of every lubrication system analysis procedure. Based on this test matrix, the transmission is tested, whereas points of interest are being recorded by cameras simultaneously. Via the video stream, the engineering team assess, if the lubrication of the bearing seems is "*sufficient"*. This binary assessment of "*ok*" or "*not ok*" is experience based and difficult to qualify decision. The assessment, whether the lubrication is "*sufficient"* or not, needs to be added to these currently *experience based decision*. The development of a more detailed solution to the visual inspection was the objective of this research project.

Due to geometrical constraints, the installation of conventional process flow meters inside of transmissions is usually not possible. Often a bypass of a lubricant supply line is established with transparent Teflon tubes to make the fluid flow visible. Such modification could dramatically influence the original lubrication condition and is not representative. Therefore, any measurement system to quantify the fluid condition has to be minimally invasive and should not disturb the initial fluid flow in a gearbox. Furthermore, the harsh environmental conditions inside require thermal stability over a broad temperature range and also chemical resistance against aggressive lubricants to any measurement probe. Observations through transparent housings in currently used gearboxes show, that the lubricant distribution is not consistent. Depending on the speed, and the acceleration in lateral or longitudinal direction, oil splashing and for example aeration in the oil sump increases. This aspect makes the differentiation between gaseous and liquid fluid conditions an essential requirement for a flow meter. Based on the listed requirements, the development of a new sensor system for a precise lubrication analysis is required.

## 3 Technology

The acronym FMwMD stands for **F**low **M**eter **w**ith **M**edium **D**etection and is the name of the patented sensor [1]. The sensor combines a thermal and an optical measurement principle and is capable of measuring the flow velocity and the temperature of a fluid. Furthermore, the sensor can detect fluid splashes as well as gas bubbles.

The flow meter is realized by using the calorimetric measurement principle, which is shown in figure 2. If the cross-section of the application e.g. a pipe is known and the flow is laminar, also the flow rate in liter per second [lps] can be calculated. The calorimeter front end consists of two PTC thermistor elements. One element acts as reference element and the other element as heater. Based on the temperature of the reference element, the heater element gets heated up by a controller. A control loop manipulates the temperature of the heater to establish a constant temperature difference between the heater and the reference element. The heat power of the heater is measured and represents the output signal of the calorimeter. When the flow equals zero, the heat power $\dot{Q}$ is at its minimum. With increasing flow velocity, more heat dissipates and the heat power also increases. Therefore, the heat power $\dot{Q}$ is proportional to the flow velocity $v_{fluid}$ of the fluid. The physical law behind this behaviour is the general heat transfer equation [2]. To get an understanding of the relations, the quasi-one-dimensional steady conditions heat transfer equation is mentioned:

$$\dot{Q}(x) = -k(v_{fluid})\left(A\frac{dT}{dx}\right) \qquad (1)$$

| | |
|---|---|
| $\dot{Q}$ | Heat power in $W$ |
| $x$ | Direction of temperature gradient $m$ |
| $k$ | Heat transfer coefficient $\frac{W}{mK}$ |
| $v_{fluid}$ | Flow velocity of fluid $\frac{m}{s}$ |
| $A$ | Area of heat dissipation $m^2$ |
| $T$ | Temperature $K$ |

A controller holds the term $\left(A\frac{dT}{dx}\right)$ constant, so it can be replaced by the Constant factor $C$.

$$C = -\left(A\frac{dT}{dx}\right) \qquad (2)$$

| | |
|---|---|
| $C$ | Constant parameter |

Therefore, the heat transfer equation simplifies as follows:

$$\dot{Q}(x) = k(v_{fluid}) \cdot C \qquad (3)$$

Due to the fact, that the heat transfer coefficient is proportional to the flow velocity of the fluid at a forced convection boundary condition, the following simplification can be introduced:

$$\dot{Q}(x) \propto v_{fluid} \qquad (4)$$

In simple terms: the higher the flow velocity gets, the higher the heat power has to be. The observed proportion between the flow velocity and the heat power is valid for one type of fluid. If there is a change in the fluid phase, for example, from liquid to gaseous, the heat power is no longer in *explicit* relation to the fluid velocity. For example, the heat transfer coefficient for stationary oil is similar to the heat transfer coefficient of high airflow. The differentiation between the fluid phase in the post-processing is not *distinct* any more. This observation leads to the conclusion that just a thermal measurement principle for multiphase flow metering is not sufficient.

For that reason, the calorimeter of the FMwMD sensor is supplemented by an optical sensor, which can differentiate between multiple fluid phases, for example, gas and liquid. The optical sensor uses the character of the different refraction indexes of liquids and gases. Contaminations or aging of the fluid does not have a critical effect on the optical measurement principle. The main elements of the optical sensor are a light emitter, a prism, and a light receiver. A light beam gets emitted and enters the glass prism. At the boundary surface of the prism to the fluid, the measurement effect of the sensor element comes into play. The fundamental function of the measurement principle is illustrated in figure 2. When the sensor is in air, the emitted light gets reflected, and the output signal is high because total refraction occurs at the boundary surface. In contrast, when the optics are in liquid, all emitted light gets decoupled, and the output signal is zero.

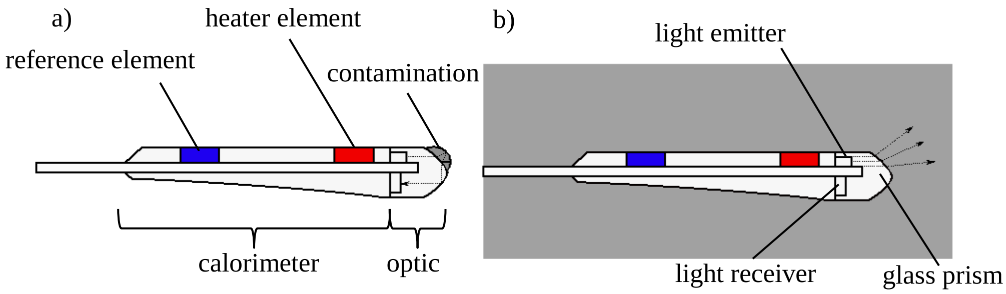


**Fig. 2.** Sensor measurement principle. a) sensor in gas with a liquid contamination on the optic b) sensor entirely in liquid

The sensor provides following raw data signals, which are then used for post-processing:

1) Temperature from the PTC element of the calorimeter
2) Heat power of the calorimeter which is depending on the flow velocity
3) The signal from the photodetector measuring the fluid phase gas or liquid

To get the flow velocity out of the raw measurement data, a look-up table is used, where the heat power and the temperature are the two inputs.

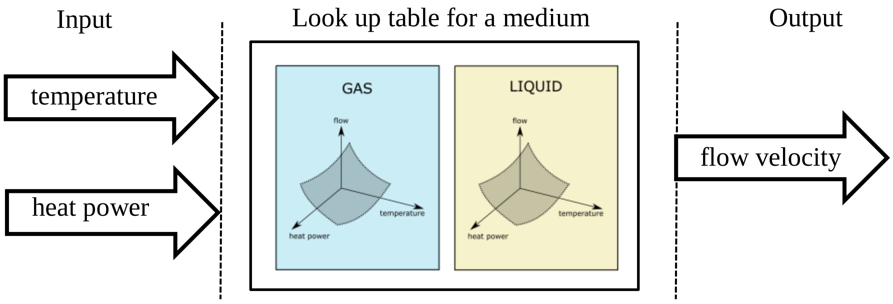


**Fig. 3.** Lookup table for data processing

The look-up table is a 3D map, which has to be calibrated for each lubricant and sensor separately. The calibration is necessary to match the fluid properties like the usually unknown thermal and viscosity parameter to the measurement system.

For any flow rate measurements, the sensor has to be fully under oil. If the measurement is performed in an open channel, the flow velocity is used to quantify the flow instead of the volume flow rate. Due to the fact, that the sensor measures the flow velocity, the pipe characteristics are needed to calculate the flow rate in out of the flow velocity. At a laminar flow profile the flow velocity is not constant over the diameter of the pipe (see figure 4.). *Therefore, the distortion of the flow profile over the diameter has to be considered for the installation point of the sensor.* The easiest way of matching the flow velocity to a the flow rate in a pipe is the calibration of the measurement setup.

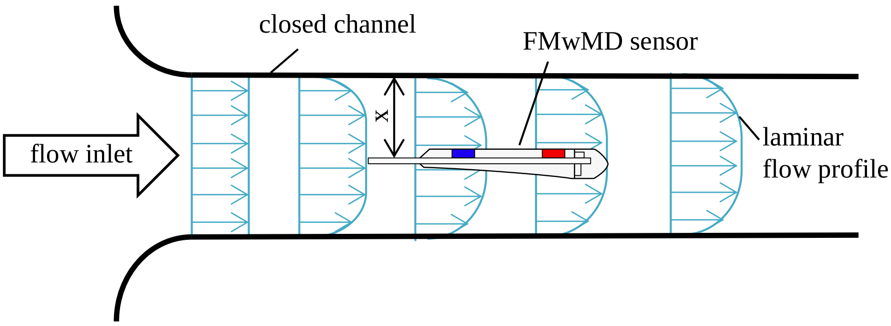


**Fig. 4.** Mounting position of the sensor in a pipe and dependency of the flow profile.

## 4 Field of application

The matrix in figure 5 shows possible applications, where the sensor could be used to validate different types of lubrication systems in the automotive powertrain development. In lubrication systems, different conditions of the lubricant are present. These conditions vary from pure oil to oil mist. Depending on the type of the lubrication system, the required, as well as the critical conditions, could vary and according to that, the sensor mounting position has to be chosen. This relation can be seen in figure 5. The examples in the red frames represent positions for monitoring critical operation conditions, whereas the green frames show the positions for evaluating the required conditions.

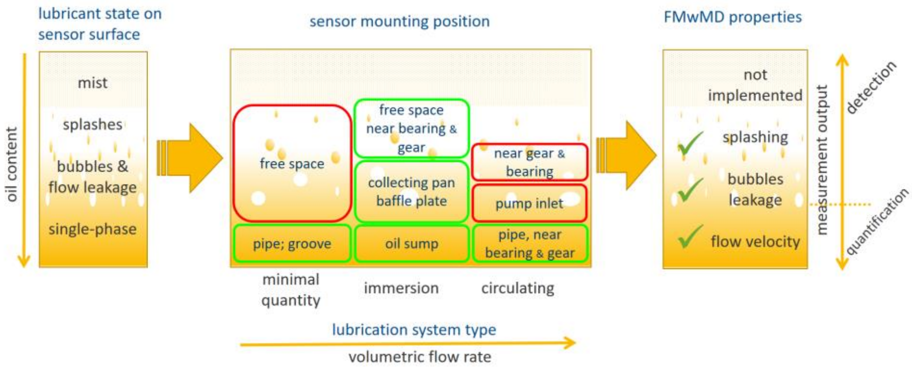


**Fig. 5.** Matrix of sensor measurement positions depended on the oil content and the lubrication system type.

The choice of the lubrication system is based on the circumferential speed of the machine component. The speed of the bearing or gear relates to the flow rate of the oil supply to the bearings or gears [3]. Therefore, a minimal quantity of lubrication has a minimum flow rate and the oil sump lubrication has the highest flow rates of the lubricant.

The design of the powertrain and the lubrication system is done by specific experience. This preliminary design should fulfi the requirements of the theoretically needed oil amount [reference]. Therefore, simulations are used to provide a rough estimation of the oil distribution. The FMwMD sensor system is used to validate the simulation and measures the lubricant conditions precisely. The measurement position has to be chosen with caution to get the best results out of the sensor system.

The matrix (see figure 5.) is classified by the oil content, which is present on the sensor surface and by the lubrication type. The oil sump lubrication is cheap, easy to implement, reliable and most commonly used in the automotive industry. It is used for a moderate circumferential speed <25m/s [4]. To ensure that the oil captures all bearings and gears, the FMwMD sensor could be used in different ways.

First, the sensor can measure the flow velocity in the oil sump of the powertrain to detect if smoothing zones for degasing the lubricant are reasonably designed. The gas/oil detector is also able to measure if there are air bubbles in the lubricant. In the region of the collecting pan, measurements after the startup could be performed to monitor lubrication in the early operating phase. In holes, grooves or drillings, the flow velocity is representative for the oil supply of the bearing. Depending on longitudinal and lateral acceleration as well as on the input shaft speed, the lubricant conditions can be quantified with the FMwMD sensor. Furthermore, the presence of oil splashing near bearings in free space can be detected with the sensor.

Figure 6 shows how the signals are used for medium detection. The blue signal represents heavy oil splashing. The red curve shows few bigger air bubbles in an otherwise laminar oil flow, indicated by the peaks. A starting lubrication, so the transition from air to oil is illustrated in the yellow signal.

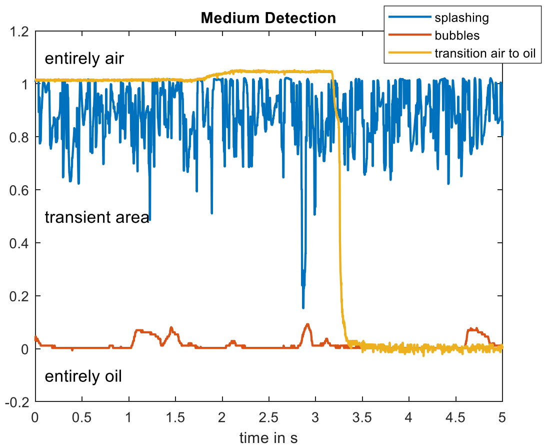


**Fig. 6.** Three exemplary FMwMD sensor measurement signals of the optical medium detection.

In case of a higher input shaft speed, often a dedicated oil pump lubrication is implemented. For that type, the sensor could be used to measure either in the supply pipes of the machine components or directly near the machine components. The fluid conditions in the supply pipes is most often a one-phase laminar oil flow. However, due to any failure, this condition could be changed by the formation of bubbles because of cavitation. The bubbles can be detected by the gas/liquid detector of the sensor. Also, the detection of a leakage in the supply line is possible. Near bearings, the time until the first lubricant is present, if the bearing is flooded or if the lubrication flow stops due to any operating condition could be detected.

In high-speed gearboxes, minimal quantity lubrication has to be applied. The detection of oil mist or especially the measurement of the oil content of the mist is not implemented in the sensor. However, the calorimeter is theoretically able to measure the velocity of the single-phase oil film, which forms inside of pipe walls in a minimal quantity dosing unit. Therefore, the detection of too much or to less oil can be used as a condition monitoring parameter and trigger an emergency stop at any critical parameter deviation. Near bearings, splashing or the accumulation of lubricants could lead to over lubrication, which could damage the gearbox within seconds.

## 5 Potentially interesting application areas

Besides using the sensor as a development and analysis tool for lubrication system design in the automotive sector, a potentially exciting use-case is condition monitoring. At testing prototypes, the sensor can prevent the device from form-critical lubrication parameters depending on the lubrication system types. The primary information, whether there is "*too much*" or "*insufficient*" oil present at the bearing, could enable early detection of damage. Therefore, the FMwMD-sensor can be a helpful device to save costs, to prevent prototype failures, and thus accelerate the development. In general, the sensor could be used in any application to monitor operating conditions and detect critical states. Another possible use case is the monitoring of coolant cycles. Current systems are using the thermal balance to monitor its condition. By implementing the measurement of the fluid flow, a much faster reaction to changes would be possible.

## 6 Comparison to traditional lubricant analysis methods

In this section, traditional methods are compared to the innovation of the IME and possible other substitute sensor methods. The evaluation criteria are composed of the in figure 7 stated aspects.

| | traditional methods | | | | | sensors alternatives | | |
|---|---|---|---|---|---|---|---|---|
| | **visual analysis** transparent housing; riser, tubes | **dye test** with luminescent additive | **endurance tests** | **temperature measurement** | new **FMwMD** | **thermal** flow sensors | **ultrasonic** flow measurement | **capacitive** measurement of fluid phase |
| **competence level** × high ≈ medium ✓ low | × | × | ≈ | × | ✓ | ✓ | ✓ | ✓ |
| **real time measurement & detection** | × | × | × | ✓ | ✓ | ✓ | ✓ | ✓ |
| **detection of bubbles; splashes; single phase flow** | ≈ | × | × | × | ✓ | × | × | ✓ |
| **flow measurement at single phase** | × | × | × | × | ✓ | ≈ | ✓ | × |
| **minimally invasive** | × | ✓ | ✓ | ✓ | ✓ | ✓ | × | ✓ |
| **system view** × poor ≈ limited ✓ good | ✓ | ≈ | ✓ | × | ✓ | × | × | × |

**Fig. 7.** Matrix to compare traditional analysis systems and possible substitute sensor systems to the FMwMD sensor.

The first criterion is the required competency level for data interpretation and the ongoing evaluation of ultimate simulation results. The most commonly used traditional method for lubrication system analysis is a visual analysis. Either a transparent housing or sight glasses in combination with a translucent bypass tube and riser, which are installed in aluminum housings, are used. Engineers are using camera systems to record oil distribution. Based on the film material, the lubricant condition assessed by the engineering team with "*sufficient*" or "*critical*". This type of evaluation requires a high competence level. The comparison of the results is difficult, especially where the threshold value for this assessment between "*sufficient*" and critical lies. Furthermore, an optical path to the evaluation point of interest has to exist. Otherwise, the unknown product behaviour remains in these not properly visible areas. An alternative solution to get an estimate about the not observable regions is a dye test. In this procedure, a *fluorescent* colour is added to the lubricant while the test is running. At the end of the trial, where a specific tilt angle and input shaft speed was used, all the oil has to be drained and the transmission to be disassembled. All machine components are inspected under ultraviolet light to examine if the fluorescence colour coats it. Out of the image form the ultraviolet inspection, the contact of oil with the machine component is evaluated.

Endurance tests require high efforts in the form of time and cost until the first results are available. In case the device under test does not fail, and no annealing colours are noticeable, the lubrication seems to be "*sufficient*" for the applied test specifications. Nevertheless, real drive operating conditions can be different from the ideal test condition on an endurance testbed.

The temperature measurements near bearings are an indicator of the operating condition of a bearing. However, the high temperature on a bearing can be caused by under- or overlubrication. In the case of overlubrication, the bearing can get damaged within a few seconds. As the temperature measurement is most often located at a small distance from to the bearing, a dead time of a few seconds is present. Therefore, the damage could already have happened without an increasing temperature at the measurement point.

The FMwMD-sensor does require no special requirements to the competence level in data interpretation when the measurement location is chosen correctly. When the test setup is installed, the threshold between "*sufficient*" and "*insufficient*" oil can be strictly defined and does not drift over time. Therefore, the FMwMD sensor provides a tremendous additional measurement data of the lubricant flow to the engineering team, which did just visual analysis up to now. Thus, the measurements are more comfortable to compare.

If a single-phase fluid flow is present in a pipe, a conventional flowmeter could be used to measure the flow rate. But to ensure a proper function, the condition that the whole cross-section of the tube is entirely under oil has to be fulfilled.

*The FMwMD measures the flow velocity in meter per second [mps] because the sensor system can be used for any pipe diameter. Therefore a quantification of fluid flow in an open channel is possible.*

If a measurement system is minimally invasive, its influence on the original test setup is minimal. By using a plexiglass housing, the mechanical stiffness and the thermal conductivity is reduced in comparison to aluminum. This restricts the transmission from being tested at high speed, and the temperature range is limited to less than 70°C. The dye test can be performed at the real transmission and is not limited to speed or temperature

The most reliable tests are endurance tests, where the original parts can be tested at high load and a wide temperature range. Additionally, the installation of thermocouples for temperature measurement does not influence the device under test noticeable.

*Due to the compact size of the FMwMD sensor with a diameter of 3mm, the disturbance of the lubricant flow is minimal.*

Compared to sensors with ultrasonic or capacitive technologies, the FMwMD-sensor is significantly more compact in size.

For that reason, the FMwMD-sensor can either be placed near the housing insight of the transmission or with an extension in free space near a gear. The next generation of the FMwMD sensor will be realized in a foil-design, which could universally be installed on housings or a rotating shaft, which is not possible with conventional sensors.

## 7 Summary and Outlook

The technology discussed in this paper is capable of measuring the flow velocity and the temperature of the oil and can detect phase shifts in the fluid. This allows the FMwMD-sensor to differentiate between gas, splashes, bubbles, and oil. With the current implementation of the measurement principle in a compact measurement probe with a diameter of 3mm, the sensor can be universally applied in a transmission. For linking more sensors together at one databus system, a CAN-bus interface for data transfer will be included in the next sensor generation, which will be available in 2020. For a more flexible application, an adhesive flexible foil sensor probe is in the design phase. This provides the advantage of installing the sensor on a curved surface as well as in holes. Furthermore, the foil is even less invasive than the probe. For measurements at rotating parts, a wireless solution including an energy harvesting system is also in development.

Based on the gained knowledge through the sensor usage at the AVL-TU Transmission Center, a standardized lubrication system analysis procedure will be established. The future of the lubrication analysis is based on practical knowledge and simulation in the early development phase. Nevertheless, the simulation of the transmission lubrication has to be validated with the FMwMD sensor system in different operating conditions on different testbeds. Therefore, this validation method reduces unknown product behaviour and therefore supports not only to improve the quality but also the safety of transmissions. The procedure for the application of the FMwMD sensor will be published free of charge on the homepage of the IME next year.

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