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Robust sensors enabling condition-based maintenance of lubricated components in locomotives and wagons

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Abstract

Digitalization in mobility is considered the key to success to increase efficiency, reliability and safety in rail transport, both track and rolling stock. "Big data" analytics are therefore implemented. In the European Joint Undertaking "Shift2Rail", tremendous efforts are dedicated to condition-based maintenance (CBM). The task of AC2T research GmbH is to enable data collection, processing and evaluation by appropriate sensor systems for online health status monitoring of lubricated components in locomotives and wagons to increase safety and availability while reducing of maintenance costs and unplanned downtime. Special attention is paid to robustness of both sensor and algorithm to meet the high demands for reliability in rail transport. Suitable sensor systems were compiled for three use cases at locomotives and wagons by the field-to-lab approach and validated for use in CBM.

Keywords: Condition-based maintenance; Online condition monitoring; Transformer; Axle box bearing; Engine; Digitalization in mobility;

1. Introduction

Still nowadays, maintenance is mainly triggered by fixed calendar days, mileage and operating hours. For the implementation of digital transformation strategies, key element of the component to monitor is an appropriate sensor (system). Regarding fluids in general and lubricants in particular, a large number of sensor concepts are available. They are mostly aiming at the measurement of electrical (conductivity or relative permittivity) or resonating (viscosity) properties comprising systems for oil degradation such as acidity and basicity, water, viscosity, wear debris or corrosiveness (Zhu *et al.*, 2017; Patocka *et al.*, 2019).

However, many sensor systems and signals still suffer from insufficient correlation with lubricant and machinery conditions and lack of robustness. In this context, robustness comprises 1) stability of the entire sensor against environmental conditions (temperature and humidity changes, vibrations and shocks), 2) reliability of sensor-based

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measurements (no signal drifts, compensation of cross-sensitivities), and 3) robust algorithms (unambiguous indication of trends and unforeseen events). Thus, robustness of a system equally concerns hardware, *i.e.*, withstanding harsh operating conditions, as well as robust software, *i.e.*, clear, and easy-to-interpret signal output. Numerous publications report on the provision of algorithms, such as trend analysis or regression analysis based on statistical approaches, to enable lubricant condition monitoring for maintenance decision support (Wakiru *et al.*, 2019). A drawback reported in the literature is the lack of providing reliable measurements as basis for prediction models. Robust sensor systems are required to deliver long-term stable and reliable measurement data. Consequently, compiling the appropriate sensor system is the key to success. Fast and reliable methods are needed to simulate the critical degradation mechanism/s, preferably by lab-based evaluation (Schneidhofer *et al.*, 2018) or laboratory bench tests (Coronado *et al.*, 2014). Thus, a high technology readiness level (TRL) is achieved in a reasonable short time before the validation in the field.

In the European Joint Undertaking “Shift2Rail”, tremendous efforts are dedicated to condition-based maintenance (CBM) with Deutsche Bahn as main driver (Shift2Rail, 2022; Dörr 2020). Here, AC2T research GmbH elaborates appropriate sensor systems for online health status monitoring of lubricated components in locomotives and wagons to increase availability but reduce maintenance costs and unplanned downtime based on the lab-to-field approach for sensor development. Special attention is paid to robustness of both sensor and algorithm to meet the high demands for reliability in rail transport.

2. Lab-to-field approach and use case definition

Three critical lubricated components – transformer, axle box bearing, and diesel engine – were selected to be equipped with sensor systems for CBM. The respective three sensor systems, *i.e.*, use cases, were developed using the unique lab-to-field approach: Starting with the requirements to monitor lubricated components, customized sensor systems are designed and assembled. The knowledge of the lubricant/machinery damage during real operation is crucial to apply laboratory-based simulations. Thus, centrepiece of the lab-to-field approach is the sensor development environment that simulates field operating conditions in the laboratory. Moreover, a significant acceleration in lubricant damaging and hence sensor development is achieved. *E.g.*, operation of a diesel locomotive for one year can be simulated in the laboratory in one week. The accelerated, realistic and reproducible simulation of lubricant damage allows the development and optimization of sensor systems in several but short iteration steps. Algorithms are typically based on linear and exponential relationships between sensor signal and lubricant property including the consideration of cross-sensitivities, in particular temperature and humidity. Thus, a high degree of development, *i.e.*, TRL up to 5, is rapidly achieved before the validation in the field. The following consecutive development steps are applied: 1) Proof of concept for the suitability of the sensor system (TRL3), 2) Close-to-reality training to elaborate correlations between sensor signal and lubricant property as well as cross-sensitivities, 3) Algorithm development, 4) Laboratory-based validation of the sensor system by execution of a test program that simulates lubricant damage under realistic or specific operating conditions (TRL4-5), and 5) demonstration of the sensor system in a field test (TRL6-7).

2.1. Use case “transformer oil in electric locomotives”

The proper assessment of the transformer oil’s condition requires a wide range of analyses, *e.g.*, see DIN EN 60422:2013-11 (2013). To establish early warning in the event of fault conditions, sensors focusing on the most relevant and critical oil parameters were the obvious solution. A quick decision at specific fault events (gas accumulation in transformer) is highly crucial to enable an immediate decision about the necessary measures. The importance of dissolved gas analysis of transformer oils is also reported by de Faria *et al.* (2015), *e.g.*, the formation of hydrogen gas (H_2) points to electrical discharges due to transformer malfunction. Sensors that monitor the transformer oil’s condition deliver the required information for such immediate decision making.

2.2. Use case “water content of greases in axle box bearings”

Water is the most crucial contamination in lubricated systems as it may damage or even destroy bearings. Besides corrosion, water is a leading cause of cavitation or metal fracture. Depending on the lubricant type and temperature, a bearing can lose 75 % of its life-time due to even low water contamination (Fitch, 2008). Critical amounts of water cause reduced lubrication or worse, bearing failure, which is signalled in advance by the humidity sensor in axle box bearings (HSAB). Knowing the water content in the axle box bearing is indispensable to ensure failsafe operation of the bearing and consequently also the wagon. At this use case, much attention was paid to the mechanical robustness as the harshest environment is given at the axle box bearing compared to the transformer and the diesel engine. Here, mechanical impacts caused by rolling over switches, crossings and rail joints directly affect the sensor mounted in the axle box bearing. Therefore, the mechanical stress was simulated under extended load conditions based on the standard IEC 61373 (2010) “Category 3 Axle mounted” to simulate relevant environments in an accelerated manner.

2.3. Use case “engine oil in diesel locomotives”

One critical component of a diesel locomotive is the engine causing a significant amount of maintenance. Therefore, the aim of this use case is to provide an online oil condition monitoring system considered for the operation in a diesel locomotive (shunting locomotive). In view of the combustion process and engine set up, additive depletion, base oil oxidation, and contamination with fuel, water, and/or soot of the oil have the greatest influence on engine performance. Therefore, the detection of chemical parameters of the engine oil is of primary importance, especially acidification. Using the above-described lab-to-field approach, a suitable sensor system was developed and evaluated together with a proper algorithm to enable CBM for diesel locomotives.

3. Results and discussion

3.1. Elaboration of critical lubricant parameters

Numerous oil analytical methods are available in the laboratory to obtain in-depth insight into the lubricant condition. As to online lubricant condition monitoring, the focus must be put on the most important lubricant parameters indicating the need for a lubricant change or another maintenance measure related to the specific application. Therefore, it is crucial to know the critical lubricant parameters of the specific application. To extract the critical parameters for the respective application, lubricant analytical reports as well as lubricant samples provided by Deutsche Bahn were analysed. Based on the findings, a suitable sensor system for each use case was compiled. Table 1 summarizes the elaborated critical parameters as well as the selected sensor principles and sensor parameters to be monitored for each of the use cases.

Table 1. Elaborated critical lubricant parameters of the three use cases and appropriate measuring parameters of the sensor systems.

Use case	**Transformer**	**Axle box bearing**	**Diesel engine**
Critical parameter	Water content Dielectric loss factor Dissolved gases	Water content Temperature	Copper corrosion Acidification
Sensor system	Loss factor Dissolved hydrogen Humidity Temperature	Humidity Temperature	Corrosiveness Electrical conductivity Relative permittivity Humidity Temperature

At transformer oil in electric locomotives, the most critical parameters of both mineral and ester oil types are water content, dielectric loss factor and dissolved gases, which serve as indicators of the transformer’s functionality and are thus implemented as parameters in the sensor system. Regarding axle box bearing, water content was identified as critical lubricant parameter, as expected. Core element of the sensor system is a humidity sensor mounted in the atmosphere of the lubricated axle bearing of the wagon. In the event of an undesired water intake to the grease, the air humidity will increase and be detected by the sensor. As to diesel locomotives, engine oil analyses revealed occasionally elevated copper content and partly higher oil acidification, which could be correlated with corrosion issues as critical damage mechanism. Therefore, key element of the sensor system is the corrosiveness sensor with a sacrificial layer corroding at a critical level of oil corrosiveness (Schneidhofer et al., 2016). Besides, electrical oil properties were used as indicator for thermal-oxidative degradation.

3.2. Laboratory validation of use case “transformer oil in electric locomotives”

Specific water contents at typical operating conditions were established at the sensor development environment composed of an alteration and sensor zone and connected by an oil circuit. Water content was controlled by Karl-Fischer titration during the tests. Based on the results, an algorithm was elaborated to determine the water content from the sensor signal for relative humidity (Fig. 1 left). Electrical discharges like arcs or sparks are a potential failure source in transformers. Possible sources are broken, or loose wires caused by, *e.g.*, vibrations during use. These discharges provoke considerable oil degradation, formation of insolubles and volatiles like hydrogen or hydrocarbons. To simulate electrical discharges in the lubricant, a relay was used, which was periodically switched to provoke arcs in the oil. The relay was therefore completely immersed into the transformer oil in the alteration zone while the oil was pumped continuously through the sensor zone. Fig. 1 right illustrates the trend of the recorded signal for dissolved H_2 during oil degradation by arcs. It can be clearly seen that the signal increased demonstrating the formation of hydrogen gas during the simulation. Robust algorithms have been produced by the elimination of cross-sensitivities, particularly temperature and relative humidity, in addition to the correlation of sensor signals and lubricant/component performance parameters. Fig. 2 left shows the dependence of the electrical conductivity on these two parameters. Fig. 2 right provides the algorithm for temperature compensation.

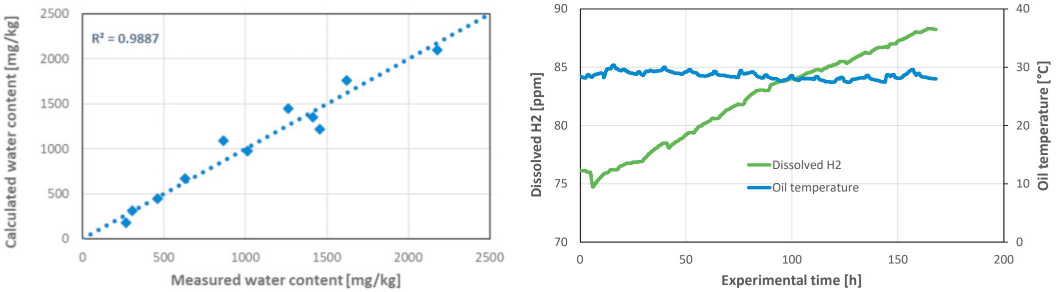
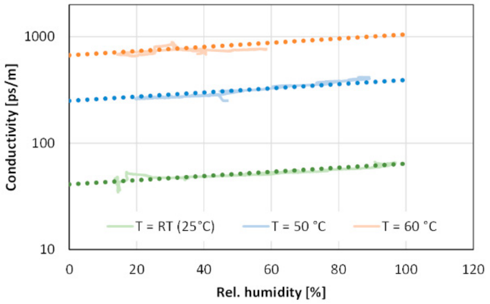


Fig. 1. Correlation between calculated and measured water content with the developed algorithm (left), trend of dissolved H_2 in the laboratory during oil arcing (right).



$$\ln \sigma_{TC} = \ln \sigma_m + TC_\sigma \cdot \left(\frac{1}{T_{Ref}} - \frac{1}{T_m} \right)$$

σ_{TC} ... *temperature compensated conductivity* $[pS/m]$
σ_m ... *conductivity measured with sensor* $[pS/m]$
TC_σ ... *temperature coefficient for conductivity*
T_{Ref} ... *reference temperature* $[K]$
T_m ... *oil temperature measured with sensor* $[K]$

Fig. 2. Compensation of temperature and relative humidity as cross sensitivities (left), algorithm exemplarily shown for temperature compensation (right).

Concluding, the chosen sensor system – as summarized in Table 1 – is suitable to detect the most critical failure patterns in transformers.

3.3. Laboratory validation of use case “water content of greases in axle box bearings”

For the laboratory validation of the sensor system for this use case, a bearing test rig modified from DIN 51350-6 (1996) (tapered roller bearing, Fig. 3 left) was used to confirm the functionality under realistic and dynamic operating conditions. Two lubricated tapered roller bearings were forced together at a load of 5 kN and rotated at a defined speed of 1500 rpm. The humidity sensor was placed in a tube that was connected to the atmosphere in the bearing test rig. A commercially available grease for railway axle box bearings in fresh condition and mixed with 1 % water was used for the tests carried out at 25, 40 and 53 °C. After each test, a grease sample was taken to determine the water content by Karl-Fischer titration. Fig. 3 right shows the correlation between the measured relative humidity to the grease water content. The surrounding temperature significantly affected the humidity measurement. The robust algorithm considers temperatures of grease and sensor atmosphere as well as grease circulation based on the measured trends.

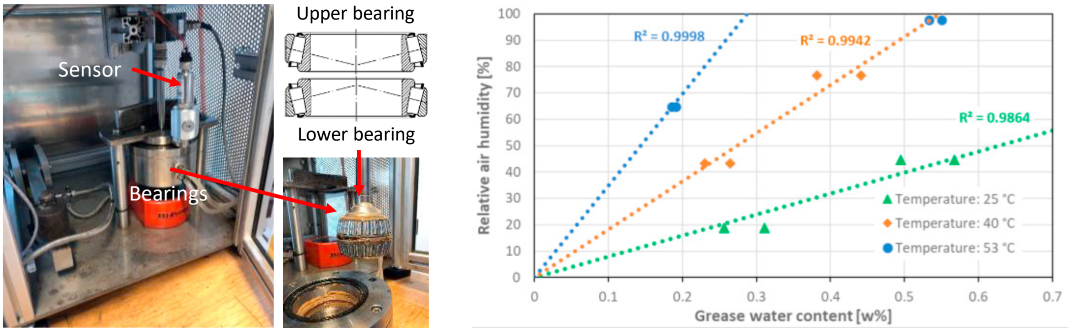


Fig. 3. Dynamic measurement system enclosing two tapered roller bearings face to face with the sensor (left) and correlation between grease water content and humidity sensor signal determined by dynamic measurements in the bearing test rig at various temperatures (right).

For the validation under relevant environment as well as later in the demonstrator, the sensor system was fixed on an extended bearing cover from PJ Messtechnik GmbH via a mounting unit as shown in Fig. 5 a. The completely mounted bearing cover including the sensors was tested for applicability in rail application using enhanced environmental conditions beyond the standard IEC 61373 “Category 3 Axle mounted”. In comparison to standard test conditions, simulated long-life tests with root-mean-square (RMS) acceleration 148 to 250 m/s² vs. 144 m/s² and shock tests with time periods of 6 ms with increasing peak load up to 1200 m/s² (in total 117 shocks vs. 18 shocks) were applied. The entire system was also subjected to climatic stress, *i.e.*, temperature (25 and 60 °C) and humidity (10 and 100 %) using a hot air dryer and an ultrasonic humidifier. The bearing cover including the sensors was mounted in the same orientation as in real application. Vibration and shocks were applied in vertical direction.

Sensor signals of relative humidity and temperature of all sensors were recorded during the simulated long-life test under enhanced and relevant climatic conditions. The sensor data were evaluated in terms of inconsistent changes or other malfunctions similar to the vibration tests discussed above. During these tests, the sensors provided reliable data and there was no evidence that they failed during the enhanced tests. Functionality and mechanical integrity remained unchanged. Therefore, the test result was “pass” for all four applied climatic conditions, which confirmed robustness.

Beside the simulated long-life test program, shock tests were applied to the entire sensor system. In total, 117 shocks were executed and therefore significantly more than given in the standard IEC 61373 with three positive and three negative shocks in each axis direction (in total 18 shocks). Also at the shock tests, the sensors delivered quasi-identical signals. Thus, the sensors provided again reliable data and there was no evidence that they failed during the tests. Functionality and mechanical integrity remained unchanged. Therefore, the test result was “pass” for the shock test at the applied climatic conditions, which again confirmed robustness of hardware and software.

Concluding, the results demonstrated the functionality and robustness of the entire HSAB system – composed as in Table 1 – in relevant environment simulated by mechanical impact test under various relevant climatic conditions ranging from normal dry to hot wet atmosphere.

3.4. Laboratory validation of use case “engine oil in diesel locomotives”

For the evaluation of the functionality of the sensor system for this use case, the sensor system was implemented in a development environment that simulated engine oil degradation. In detail, an artificial alteration device (alteration zone) simulated entire engine oil drain intervals within short time and was combined with an oil circulation system having implemented the sensor system (sensor zone). The oil was pumped continuously to the sensor zone and back to the alteration zone. This way, the sensor signals depending on the degree of oil degradation were continuously recorded. For algorithm development, regularly taken oil samples were analysed to correlate the sensor signals to the corresponding oil condition determined by conventional oil analytical methods.

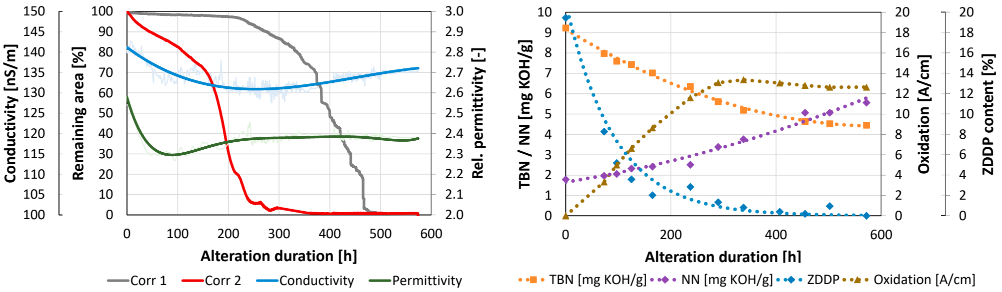


Fig. 4. Trend of sensor signals (left) and oil parameters (right) during simulation by artificial alteration of a diesel engine oil.

Fig. 4 left illustrates the trends of the recorded sensor signals during artificial alteration of a common engine oil used in diesel locomotives, and the analyses of regularly taken oil samples are shown in Fig. 4 right. As can be seen, the signals of the corrosion sensor (Corr1 and Corr2) were characterised by a sharp signal drop after specific times indicating a specific level of corrosiveness. The electrical conductivity showed the typical bathtub curve. The signal decrease indicated the consumption of additives, *i.e.*, TBN for the base reserve and ZDDP for antiwear additive depletion. This decrease was followed by a signal increase owed to the significant formation of degradation products, expressed for example by NN for the amount of acids. The signal for relative permittivity exhibited a drop in the first 100 h, which can be attributed to antiwear additive depletion. Afterwards, an increase till around 300 h was noticed followed by a plateau till the end of the test. This observation was in accordance with the trend of the oxidation that also remained constantly in the last phase of oil degradation.

Concluding, the sensor signals can be well correlated to both oil condition and sudden events. This confirms reliable measurements with the sensor system (Table 1), which form the basis for the establishment of a robust algorithm.

3.5. Field validation of the sensor systems

3.5.1. Field validation of use case "water content of greases in axle box bearings"

For the field evaluation of the HSAB system, the completely mounted system was installed at the axle box of an Y25 bogie of a freight wagon (Fig. 5 b). As wagon onboard unit for acquisition and storage of the sensor signals, the Wagon Tracker Advanced of PJ Messtechnik GmbH (2019) was used. The HSAB system was validated for a period of 10 weeks. Fig. 5 c exemplarily shows the trend of the recorded signals during a drive from Graz to Salzburg (Austria). The sensor system provided reliable signals and the expected trends, and no abnormalities were detected.

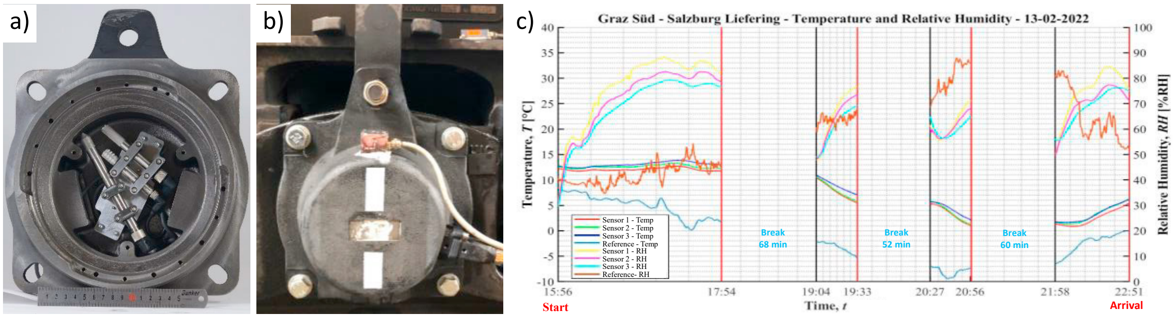


Fig. 5. a) HSAB system integrated into the axle box bearing cover, b) HSAB system in bearing cover at axle box, and c) trend of recorded sensor signals exemplarily shown for one drive.

Therefore, the HSAB system is suitable and robust to work in the harsh environment at the axle box and thus is a means to provide a valuable contribution to the reliable and safe operation of freight wagons.

3.5.2. Field validation of use case “engine oil in diesel locomotives”

The developed sensor system, see Fig. 6 left, was implemented into three diesel locomotives of type BR233, BR294 and BR362 operated by Deutsche Bahn. Fig. 6 right exemplarily shows the trend of the processed sensor signals.

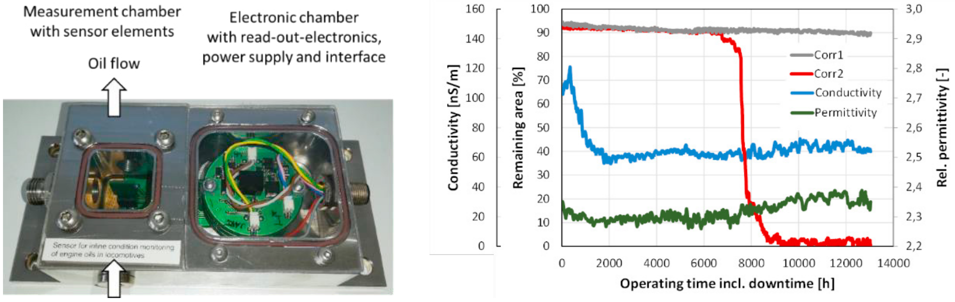


Fig. 6. Sensor system (with transparent cover to show the sensor setup) for engine oil (left) and signals recorded during the field test carried out with Deutsche Bahn (right).

Most important at the processing is the compensation of cross-sensitivities such as temperature effects by application of the developed algorithm. Characteristic trends of the processed signals observed were similar to those in laboratory validation (Fig. 4 left). As to electric conductivity, a drop at the beginning was noticed due to additive depletion followed by a slight increase due to further engine oil degradation. Relative permittivity also exhibited a slight increase during the observed period. Most interest attracted the sharp drop noticed at the corrosion sensor (Corr2) indicating a certain level of acidification. As in the laboratory, the sensor indicated the onset of acidification in the same explicit and fast way in the field.

Concluding, the sensor system for engine oil delivered reliable and stable signals in all three diesel locomotives. Characteristic signal changes were observed that referred to specific lubricant conditions. Therefore, the developed hardware and software are suitable for the railway application.

3.6. Next steps towards CBM

Being the largest advantage of the lab-to-field approach, a rapid development up to TRL5 in the laboratory was enabled for the three use cases, which are completely different in the operating conditions and requirements for online condition monitoring. Another tremendous advantage is the (pre-)development of an algorithm to continuously provide the operator with the health status of the lubricated components, especially to alert in the event of abnormal behaviour. Although the lab-based simulation of real operating conditions is somewhat limited, the high degree of development already achieved in the laboratory lays the foundation for the finetuning of the algorithm based on data collected during field validation, in particular trend analysis and setting of thresholds. They are the basis for CBM, thus the planning of maintenance tasks on demand. Furthermore, detection of abnormal behaviour by the sensor systems at an early stage allows for immediate measures. Consequently, maintenance efforts can be optimized, even reduced due to lower damage evolved since measures are early taken, while increasing safety of railway operation and availability of locomotives and wagons. Eventually, a significant extension of lubricant change intervals, as achievable in industrial facilities, additionally contributes to maintenance cost reduction.

CBM opens a new way of operation in railway applications. Therefore, in the first period of implementation, detection of abnormal behaviour of lubricants and lubricated components by the sensor systems, thus serving as alert systems, was defined as major target. The implementation of CBM via the sensor systems can be done by the manufacturer of locomotives by installation of the sensor system in the oil circulation line of the transformer or diesel engine, preferably via a bypass. As to the HSAB system, implementation is realized in the bearing cover. Energy supply is either provided by the locomotive (use case “engine oil in diesel locomotives”) or an energy harvester (use case “water content of greases in axle box bearings”). A major advantage of the developed sensor systems is that they can be installed in already-in-use locomotives or wagons by retrofit. Moreover, data acquisition frequencies for online condition monitoring can be widely adapted to the anticipated changes in lubricant properties over time. Eventually, flexibility in kind of data transmission (cable or wireless), enables good compliance with the operator's specifications.

The developed algorithm is implemented in the on-board unit of the locomotive or wagon, which also reads the signals and stores signal data from the sensor systems. Alternatively, a separate control unit can be implemented, which reads the sensor signals on a continuous basis, executes the developed algorithm for signal interpretation and provides online status signals to the on-board unit, to the train driver or directly to a fleet management system. Realization of decision-making for CBM is currently discussed in two ways: 1) by the engineer, as s/he has comprehensive access to the data and the necessary know-how; 2) by the train driver in urgent events, as the engineer is not always available for immediate decisions.

4. Summary and conclusions

The lab-to-field approach moves robust sensor designs swiftly to a higher TRL, thus keeping the need for field validation at a lower level and consequently enabling early market entry and use, as illustrated by three use cases related to transformers, axle box bearings and diesel engines. Laboratory and field validation confirmed robustness of both sensor systems and developed algorithms as well as their suitability for lubricated components in railway applications. Future work will focus on further generation of field data to finetune the algorithms originally established on laboratory data. Then, trend analysis and defined thresholds are applied to move from fixed-interval to condition-based maintenance of lubricated components in rolling stock.

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