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New monitoring system for direct operating surveillance of con-rod bearings

Tribology

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ABSTRACT

According to SOLAS option 1, operational monitoring of con-rod bearings is usually realized by oil-mist detectors, monitoring all components in crank drive of individual cylinders or in the whole crankcase. For a more detailed analysis of crank drive tribology, specific information of high-loaded con-rod bearings are necessary. Splash-oil systems are partly not reliable, as maritime accident investigations have shown. Direct surveillance methods with radar or RFID for moved slide bearings are complicated and expensive. A new monitoring principle and its development to a functional prototype system will be described.

Physical method for this contactless and non-optical monitoring of con-rod slide bearings is the temperature-related behavior of ferromagnets and its detection by fixed mounted magneto-inductive sensors. Neodymium magnets mounted at the backside of bearing shells are heated rapidly while bearing damages start, resulting in decreasing field strength.

Development work for realizing a safe distance between con-rod and sensor, beginning with basic experiments for the installation of sensors in a ferromagnetic crankcase and the position of magnets inside steel-made con-rods will be described. With special kind of magnets installation, the magnetization of bearing shell and therefore possible aggregations of abrasion particles at the inner surface of the bearing shell have been avoided.

Essential functionality of this measuring principle was considered without using test engines at several cooling-down experiments at preheated testbench-models in the dimension of real con-rods of medium-speed diesel engines. With optimised design a response time of about 4 sec was proven even at tests with temperature deviations of less than 0,5 K/sec. Influences of magnetic attenuation and countermeasures are described.

First tests at a large single-cylinder engine (DB = 160 mm) with magnets, fixed mounted and heated by the cylinder liner demonstrated the influence of conditions inside crankcase to the used sensor. Special thermal insulation and cooling of sensor had to be made to avoid drifting signals. Compressed air for sensor cooling was used without entering crankcase.

After this verification work, the adaption of the sensor system inside the chosen test engine was designed. Experimental work at the test engine was carried out while pre-heating and in engine operation. At several engine speeds between 150 and 1,200 rpm, the functionality of this new method for monitoring of moved slide bearings was demonstrated by rapid variations of lube-oil temperatures. Influence of engine speed had to be considered. Functionality was proven, but the low distance of 6mm between sensor and magnet as well as its low sensitivity seemed to be not competitive. A new sensor generation and complete controller system were developed within this project. In similar engine tests, a minimum(!) distance between sensor and magnet of 26mm had to be kept avoiding overmodulation. Beside general function with competitive distances, the correct implementation of signal processing at controllers' software was proven. A safely analysable sensor sensitivity of 0,5 V / 10 K, including a sufficient resistance against electromagnetic interference could be achieved. Response time due to temperature deviation is below 10 sec. Beside the achievement of the technical goals, a system price target of less than 1,000 €/cyl. (for 8L-engine) including class approval could be proven.

1 PROJECT MOTIVATION

Crankcase explosions at large Diesel and gas engines, occurred by a formation of critical lube-oil/air-atmosphere inside crankcase, and their direct consequences of engine breakdown, destruction of crankcases and fire inside the engine room are one of the most dangerous situations for crew, vessel and land-based power generation.

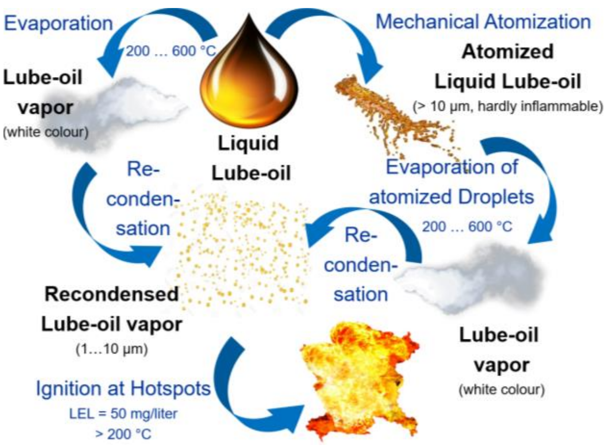

Figure 1.1. Mechanism of lubrication-oil ignition

Common theory for the formation of this critical atmosphere is the atomization, evaporation and recondensation of lubrication-oil droplets via two different pathways (Fig. 1.1). At temperatures >200 °C lube-oil is evaporated directly from liquid phase or after mechanical atomization. Atomized droplets with diameters >10 µm are hardly inflammable. Only re-condensation of this vapor forms droplet sizes <10 µm, inflammable at hotspots >200 °C. The concentration of 50 mg/liter, often given for lower explosion level is depended on droplet size distribution. Corresponding shockwave should be relieved by relive-valves at the crank-doors. Versions with flame-catchers would prevent fire-penetration into the engine room.

After primary explosion the crankcase pressure can be below atmospheric value. If the relief-valves do not close correctly afterwards, fresh air will enter the crankcase. An even stronger secondary explosion occurs.

Beside direct contacts between flames inside cylinder and lube-oil via worn piston-crowns, hotspots can be formed by tribology failures at piston/cylinder-liner, crankpin and its bearing shell, main bearing/crankshaft or inside highly loaded con-rod bearings respectively crossheads. Based on an older data collection by Lloyds Register (LR) and its market share approx. 120 crankcase explosions onboard seagoing vessels were estimated. Only in approx. 15 % of recorded cases low-speed 2-stroke-engines were affected [1].

By statistics of DNV [2] and LR [3] con-rod bearings were concerned in approx. 14 % of all reported damages at medium-speed engines and 17 % at high-speed. Beside the questions of safety for engine operation, vessel and crew the economic aspects of bearing damages must be considered. While damaged bearing shells are easily and inexpensive to exchange, possible secondary damages at crankpin, irreparable by grinding within the machining allowance in diameter of e.g. 5 mm, become a massive economical problem. Delivery times for replacement of crankshafts of approx. 24 months in boom phases as well as their costs are extremely problematic. A consequence may mean in an operation-breakdown for months. This financial loss (e.g. default insurance for 99 days) endangers small and medium-sized shipping companies.

For these reasons of safety, crankcase monitoring by oil-mist detectors (option 1) or of bearing temperatures (option 2) is required by SOLAS for all engines onboard with an output of $P_e \geq 2.25$ MW. A combination of options 1 and 2 can enable faster localization of the cause of the oil mist alarm or the identification of false alarms. Fixed main bearings are easily to monitor by temperature-probes. For moved bearings at the con-rods splash-oil systems are used, which monitor the bearings indirectly via the temperature of lube-oil that is deposited and collected on the crank-doors. Monitoring systems, directly observing the conditions of moved bearings at con-rod and crosshead by radar-waves [2], RFID-technology [4] or surface acoustic [5] are cost-expensive, require too small sensor distances or are not available commercially anymore.

For these reasons, a new sensor system was developed, measuring the conditions of moved bearings inside crankcase directly. A reliably functional prototype system for temperature monitoring with sensor distances above 26 mm and its physical operational principle will be introduced. The price target on the market of 1000 €/cyl. (for 8L) including classification ensures an economic pathway for engine manufactures and operators.

Extended investigations for optimizing the very price-attractive splash-oil monitoring should allow cost/benefit-considerations. Although knowing about false alarms, wrong installations and poor maintenance the replacement of oil-mist detectors as a standard solution for overall crankcase monitoring, observing gear-drive and tribology of cylinder-liner additionally, was never intended within this development project.

2 CONSIDERATIONS WITH SPLASH-OIL SYSTEMS

According to a non-representative survey of technical crew at 120 vessels in 42 % of these cases engines were equipped with oil-mist detectors as the only preventive measure. Approx. 55 % of these vessels were equipped with some kind of bearing monitoring (main and/or con-rod) and for 3 % bearing temperature monitoring was the only method of protection [6].

An example for failed prevention by splash-oil system is given with [7]. Massive engine damage with destruction of crankcase and fire inside engine room was not inhibited by this safety device. Collected oil, splashed-off from con-rod and its temperature were not sufficient for triggering alarm. Wreckage parts of crank-drive destroyed the temperature probe for splash-oil at this cylinder, registered by engine monitoring system. Main engine shut-down was caused later by low lube-oil pressure at turbocharger.

2.1 Movement of Lube-oil Droplets Inside Crankcase

An in-house development step was attempted to consider the potential for improvement of this measuring principle [8, 9]. This work began with an optical analysis of the conditions in the crankcase of a large externally charged single-cylinder Diesel engine FM16/24 “Norbert” (240 mm stroke, 160 mm bore, output 101 kW @ 1200 rpm, conventional mechanical fuel injection system) using the power unit of the smallest HFO-burning engine in the market. Engine and its operational and emissions behaviour were described in [10, 11, 12].

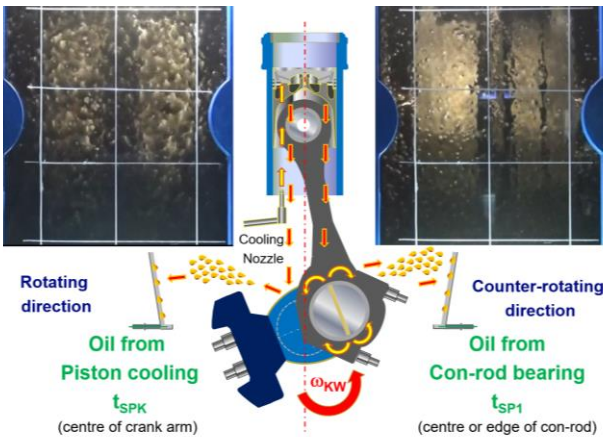

Figure 2.1. Optical investigations of droplet-distribution

The crank-doors were temporarily replaced by transparent polycarbonate. The aim was to identify defined splash marks and to assign to certain components. Even at lowest engine speed, it became clear that the oil-droplets at crankcase-cover in the direction of rotation mainly occurred by piston cooling. So, an installation of collecting device for monitoring of the con-rod bearing was advantageous at opposite side. To observe the piston tribology, a position at the crank-door in engine rotation is essentially. The collecting device at this crank-door should be mounted in the horizontal centre of a crank-arm.

Video sequences were taken. Even at speeds below 50 % of nominal speed no defined lines of droplets splashed-off were detected. Mainly cooling-oil, returning from piston was sputtered by the rotating crank-arms and sprayed finely dispersed to all inner crank-door surface. By reasons of safety no higher engine speeds were tested (Fig. 2.1). In parallel thermography of the crank-doors showed areas with slightly lower surface temperatures at horizontal position of con-rod’s centre. With respect to the thermal isolating effect of the crank-doors material these findings were confirmed by measurements with 5 temperature probes, installed at the inner surface of crank-door at counter-rotating side.

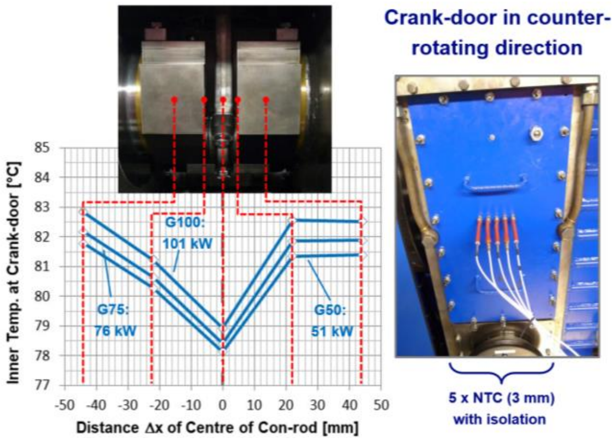

Figure 2.2. Sensoric investigations of droplet-distribution

Based on thermography, for long-term experiments the crank-door in counter-rotation was equipped with five NTC-sensors, penetrating the crankcase by 2.5 mm (Fig. 2.2). As positions for the sensors, the temperature minima from thermography pictures, the centre of the connecting rod and the centres of both crank-arms were chosen. In steady engine operation at full engine speed n_M = 1202 rpm temperature minima in the centre of the crankarm were measured regardless of the engine load. With the assumption of higher oil temperatures from piston cooling and the results from the video experiments, these minima were interpreted as splash-line from the con-rod bearing. This position was defined for the collecting device for the con-rod bearing.

2.2 Layout of Splash-oil System

For all versions of collecting device, a compromise was found between low heat capacity and safety against vibration fracture with a 2 mm panel thickness. The shape of the finally used collecting line as a V-shape promotes the collection of droplets in its centre and thus the rapid drainage into the collecting pan. The height of the line corresponds approximately to the piston stroke. A vertical inclination of 10 degrees prevents dripping past the collection pan. Its volume was set at 10 % of the lines volume. A drain lock ensures oil level on the NTC (d = 3 mm) even in rough seas and prevents unwanted temperature gradients due to the usually warmer crankcase atmosphere. With a PTFE-insert in the guidance, the NTC is thermally insulated. Its diameter guarantees long-term durability. Design and arrangement of splash-oil collecting device is shown in Fig. 2.3.

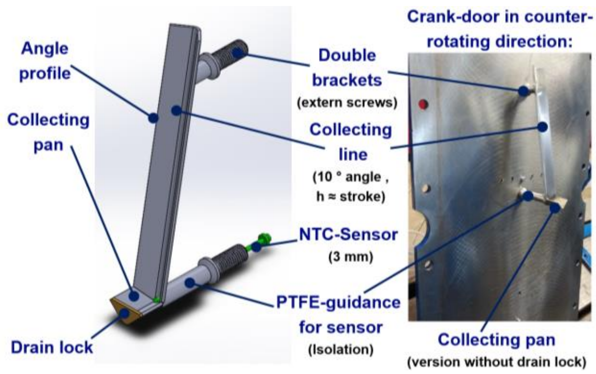

Figure 2.3. Developed splash-oil collecting device

2.3 Experiments with Splash-oil System

For experiments with different engine loads at constant nominal speed (n_M = 1200 rpm) the start of fuel delivery and the charge-air pressure were varied systematically to enlarge the load of the con-rod bearing by raising firing pressures.

Due to a modified injection timing, advanced by -2 and -3.5 °CA from standard setting, the firing pressures were enlarged by 10 and 15 bar at load point G85 (P_{eZ} = 87 kW @ 1200 rpm). Reaction of Splash-oil temperature was low with +0.2 K at -3.5 °CA and +0.4 K at -2 °CA. At all load-points there was even no tendency recognisable. By 10 % enlarged charge-air pressures resulted in 16 bar higher peak pressures at load-point G85. With explicit tendency the splash-oil temperature decreased by approx. 0.5 K at all loads (Fig. 2.4, top). In parallel to the intended higher bearing load the higher charge air pressure lowers the combustion temperatures. Despite all ideas for the design and the position of collecting devices the influence of the lube-oil re-flow from piston cooling was dominating.

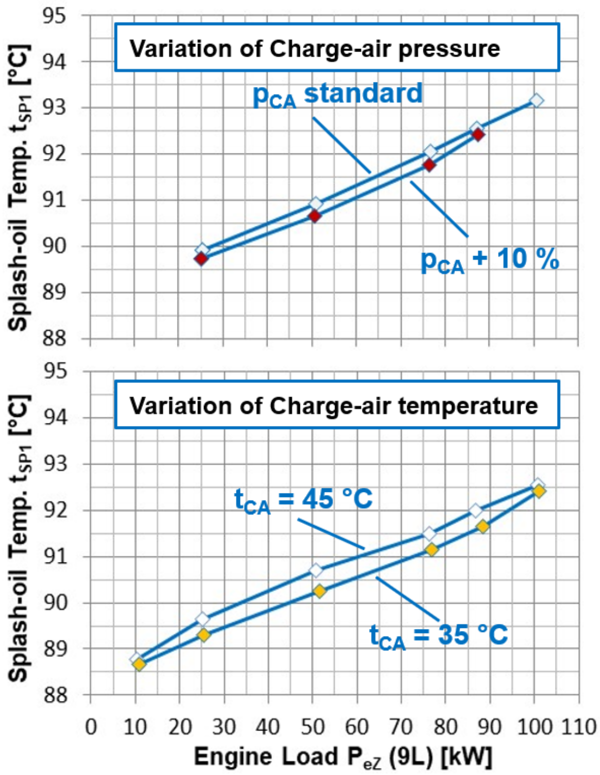

Figure 2.4. Experiments with splash-oil system

To approve this perception, the charge air temperatures were decreased by 10 K (Fig. 2.4, bottom). No effects to the bearing load were expected. Firing pressure in cylinder kept constant, but splash-oil temperatures decreased by about 0.5 K due to the reduced gas temperatures during combustion in cylinder with a clear tendency at all load range.

Sometimes splash-oil systems are said to be able for a faster response than oil-mist detectors due to its working principle close to the root-cause and the position of sensors. To proof that assumption an older opacimeter for exhaust gas was converted to oil-mist measurements and installed at the test-engine. With all limits of the externally charged single-cylinder engine, a load step from 50 to 25 % at full speed within 20 sec was realized (Fig. 2.5). While opacity inside crankcase measured by an (imperfect) opacimeter decreased immediately, the reaction of the splash-oil system was delayed and poor. Similar results of [13, 14] were confirmed. Consequences of electric interferences to the signal as well as small mounting anomalies for the tight setting of alert limits must be considered.

By [7] alarm limits of +15 K above nominal lube-oil inlet temperature and +2 K mean-value deviation of all cylinders were given. A signal-tuning of all splash-oil temperatures to the mean-value at high load seems to be necessary after installation.

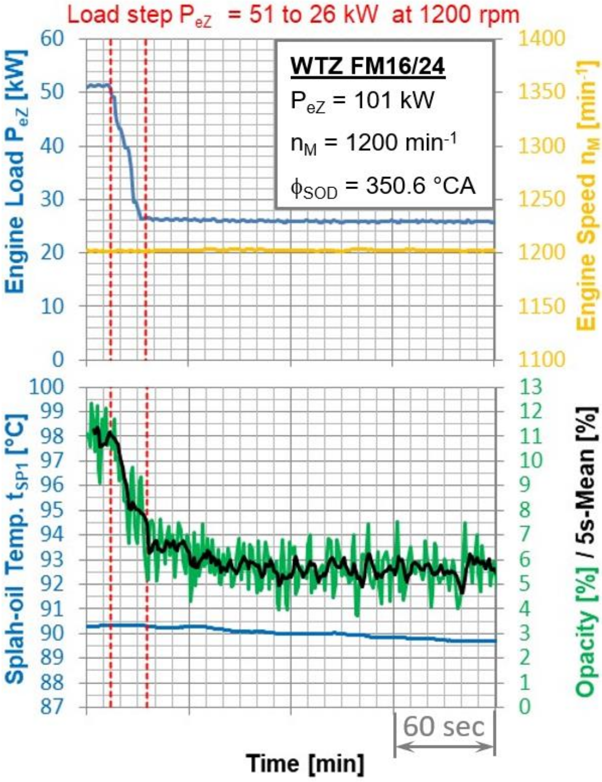

Figure 2.5. Transient experiments with splash-oil

2.4 Analysis of Lube-oil distribution

For understanding these results, drain measurements of oil-flow distribution inside the crankcase were carried out with several oil drain-pans, especially designed for each lubricated component (Fig. 2.6). The volume flow of the piston cooling was measured at the cooling oil nozzle. Stopped engine was preheated to the standard oil- and water-temperatures.

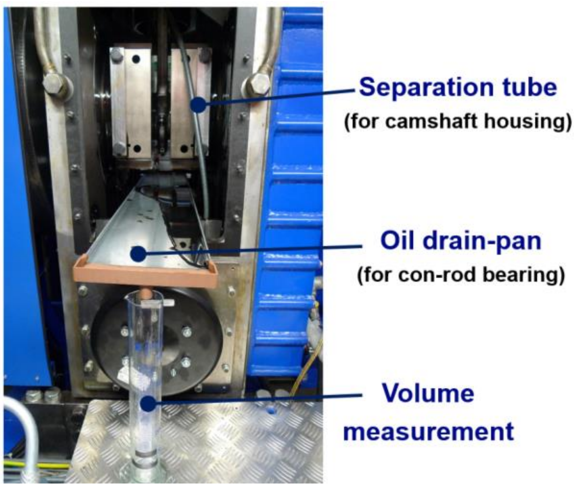

Figure 2.6. Measurements of lube-oil distribution

Results of these drain measurements are shown in Tab. 2.1. The drained lubrication oil at the con-rod bearing in that table is quantified for crank positions "90 °CA". Even the relation of <3 % between lube-oil, returned from con-rod bearing and the piston cooling shows, that even further design steps will not improve the dominating influence of the piston cooling.

Table 2.1. Results for lube-oil distribution

Component	**Flow [l/min]**	**Flow [%]**
Piston cooling	6.63	28.30
Con-rod bearing	0.18	0.77
Main bearing 1	5.87	25.05
Main bearing 2	3.47	14.81
Camshaft	7.28	31.07
Summary	**23.43**	**100.00**

2.5 Conclusions from Splash-oil Experiments

Based on these results, the effectiveness of the splash-oil system at least for crankcase monitoring of the used test engine must be categorised as critically without an additional oil mist detector. Even with all steps of optimization the dominance of piston cooling to the splash-oil monitoring was still identified. The sensibility of splash-oil sensors to changes in engine operation is considered as delayed and weak. A direct contactless monitoring of con-rod bearings (additionally to oil-mist detectors) would improve the operational safety for main and auxiliary engines onboard vessels as well as for stationary powerplants, running 8000 hr/year at highest loads.

Regarding the methodology of this investigation, it must be noted critically, that a test with a provoked con-rod bearing damage was not carried out due to risk of a total loss of the engine. For all engine types with cooling-oil supply for the piston via bores inside con-rods no statement is given by this investigation. Analogous experiments must be carried out for reliable results.

3 BASIC DEVELOPMENTS OF A NEW SENSOR SYSTEM

3.1 Physical Principle

For temperature monitoring of moved components inside crankcase a contactless and due to oil-mist non-optical physical principle will be necessary. The moved part of this system must be passive without any voltage supply to ensure long-term operation with a minimum of maintenance. With respect to demands of engine manufactures and operators an extensive arrangement of signal lines inside crankcase must be avoided. Analogue to main bearing monitoring and to ensure exchangeability of bearing shells even in case of retrofit solution no additional machining of commercially available bearing shells should be necessary. Temperature of bearing must be recorded at the backside of the steel supporting shell. A sufficient distance between sensor and monitored component ensures a save operation with respect of tolerances, mechanical vibrations and thermal expansions.

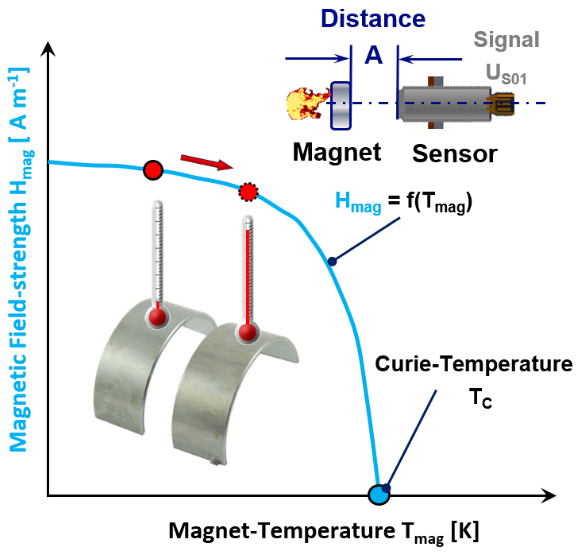

Figure 3.1. Magnetic Temperature Measurement

As physical basis for the new measurement method the Curie/Weiss-law was chosen (Fig. 3.1), which describes the dependency of magnetic field strength of its temperature. While heating-up a ferromagnet the field strength decreases linearly over a wide range. At a constant distance A between the magnet and a fixed mounted magnetic field sensor, this results in a linear relationship between the magnetic temperature T_{mag} and the signal U_{S01} of the sensor. If a decreasing sensor characteristic (= increasing sensor signal U_{S01} at a decreasing magnetic field strength H_{mag}) is also selected, a direct linear relationship between temperature of the magnet and the sensor signal is given.

Neodymium variants with the highest field strengths are suitable as magnets. Their operating temperature is specified as a maximum of 120 °C, which is sufficient for the operation-monitoring of bearing shells in large Diesel and gas engines. If higher operating temperatures should become necessary, samarium/cobalt materials can be considered as an alternative, but their temperature characteristics are advertised as particularly stable, which is contrary to the intended use.

In case of an initiating damage the moved bearing shell will be heated up and this way the near by mounted magnet, too. Its magnetic field strength decreases. Field strength is transferred with the speed of light, so that a minimum time of contact at visual axis per engine revolution would be sufficient for signal transport to the fixed (e.g. in the crank-door) mounted field strength sensor, which can be supplied by electrical wires from outside of the crankcase.

3.2 Sensors Behavior in Ferromagnetic Surroundings

For realization of this concept, the development work began with examinations of influences of the installation of sensors and magnets in a ferromagnetic crankcase and con-rod. To accelerate the work these experiments were carried out with a sensor ("Sensor01"), commercially available and in parallel with the development of an own new sensor type, especially designed for the requirements of crankcase monitoring.

This Sensor01 featured a negative characteristic, which became manifest in decreasing voltage signals at rising magnetic field-strength. By supplier of this commercial field-strength sensor the installation in a non-ferromagnetic support was strongly recommended. Several static tests have shown that it can also be mounted in steel or spheroidal graphite iron, with the sensors head protruding a few millimeters from inner surface of crank-doors. Despite of this finding the crank-doors of both possible test-engines were replaced by aluminum ones as often used in field due to weight.

To reduce the financial effort the basic tests were not carried out with a metal-cutting machined real con-rod, but with a steel-ring in the approximated dimensions of the lower part of the con-rods of both possible test-engines (Fig. 3.2).

Tests were carried out with different magnet-dimensions and materials. Fig. 3.3 shows results with a neodymium magnet in the dimension of 6 mm in diameter and length.

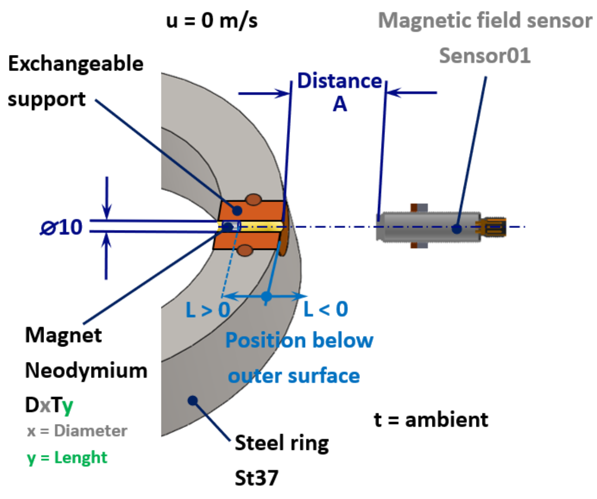

Figure 3.2. Installation optimization of the magnets

As expected, the voltage difference by presence of magnetic field decreases with larger sensor distances A. Also, a position L of the magnet below the outer surface decreases the sensor signal rapidly, so that installations inside the hole drilled to the lower con-rods eye is nonsensical. This way the temperature must conducted by a copper-liner from the bearing shell to the magnet, installed at the outer surface of con-rod. This also eliminates the risk of metallic abrasion accumulating at the inner side of the bearing-layer, made of white alloy. An even stronger signal was generated by magnets standing some mm out of the steel ring.

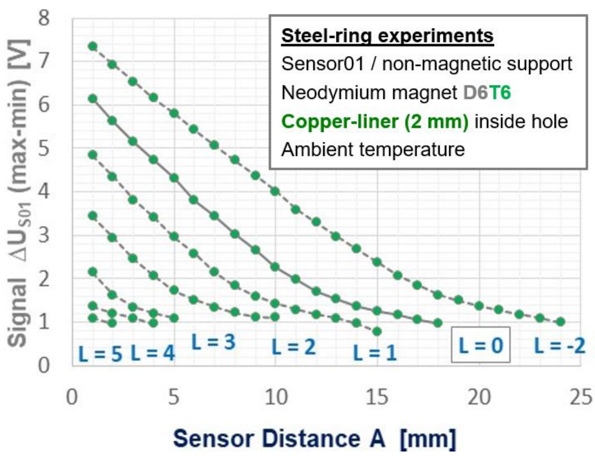

Figure 3.3. Behaviour of the magnets in steel ring

Design of copper liner and its position was further optimized (Fig. 3.4). By introduction of a bevel at the outer side of steel ring the signal could be strengthen by approx. 10 %. Down to length of magnet of T = 6 mm no significant decrease of field strength was observed.

For further examinations the dimension D6T6 was fixed with respect of the higher heat conductivity of copper (λ_{Cu} = 399 W/m K, $\lambda_{Neodymium}$ = 9 W/m K). Copper liner was filled-up from the inner side of the steel ring to the magnet with a cylindric copper stick to enlarge the heat transfer from inner surface to the magnet.

3.3 Dynamic experimental basic investigations

With this optimized geometry extensive dynamic investigations were carried out on model structures, moved by a turning machine. Fig. 3.5 shows the test setup of the latest version [15, 16].

To check the basic function of the new sensor system, steel ring with the magnet installed was preheated to the maximum bearing temperature of approx.120 °C and clamped directly in the three-jaw chuck.

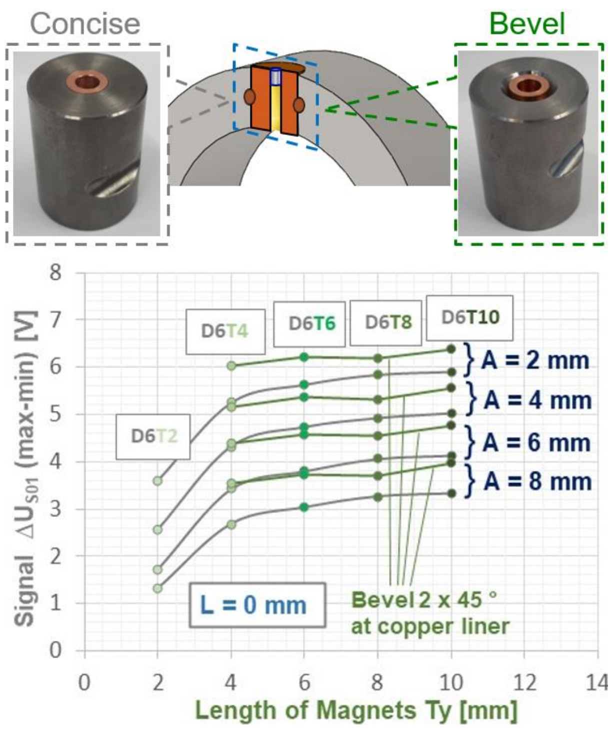

Figure 3.4. Optimization of geometry

The turning machine was operated at different speeds according to the circumferential speed of real medium-speed engines and cooling-down of the steel ring was measured. Due to the oil-free atmosphere at the turning machine, a reference temperature could be recorded contactless with 1 Hz by an IR-sensor. The magnetic field sensor was positioned with the support of the turning machine and its raw signal U_{S01} was recorded with high frequency of 100 kHz by a ScopeCorder.

By post-processing the minima of sensor signals were extracted for each revolution and stored with its timestamp (Fig. 3.6). The signal minimum of U_{S01}

during each rotation should be proportional to the temperature on the inner side of the steel ring t_{IR}. Galvanic insulation of all test equipment and application of a low-pass filter for sensor's raw signal minimized the influence of electromagnetic disturbances.

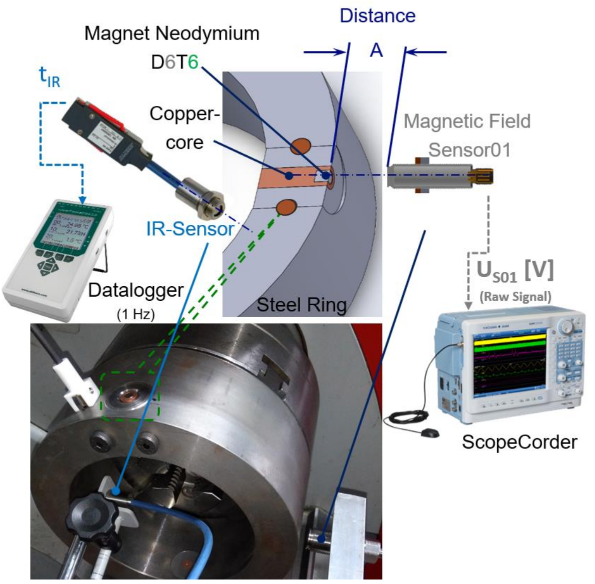

Figure 3.5. Dynamic experiments at rotating model

Fig. 3.7 shows the result of such cooling-down experiment. Steel ring and magnet were pre-heated for 36 hours at 120 °C. Cooling down phase was measured as described. Due to limited RAM capacity of the ScopeCorder the high-frequency measurement had to be interrupted in between. Signal lines of sensor signal U_{S01} were smoothed by a 4 kHz low-pass. The minima of the sensor signal U_{S01} and the reference temperature t_{IR} correlate quite well.

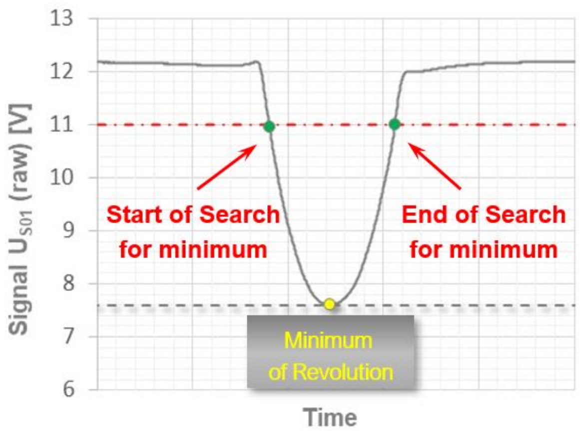

Figure 3.6. Post-processing of sensor signal

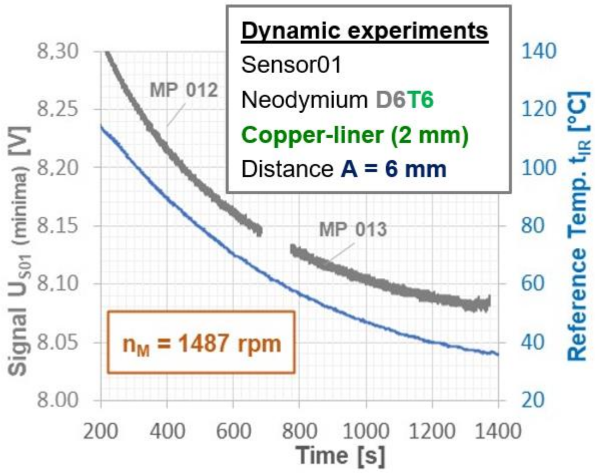

Figure 3.7. Results of dynamic experiments

These experiments were successfully carried out at various speeds up to circumferential velocity of 21 m/s. Especially electromagnetic interference from the power grid and the surrounding machine tools were problematic. These problems could be solved by comprehensive galvanic isolation.

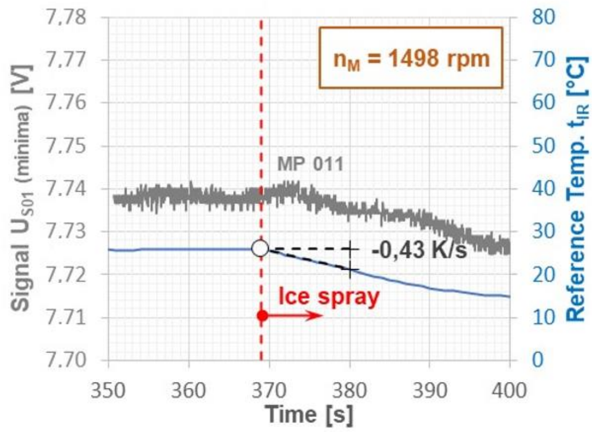

Figure 3.8. Time response at dynamic experiment

In order to determine the dynamics of the used experimental setup with special regards to the detection of fast temperature gradients an ice spray was used. The negative temperature gradient at inner surface had to be conducted by the copper-core to the magnet. Resulting deviation in magnetic field strength was detected by the sensor at the outside of the steel ring (corresponding to the outer surface of big-ends con-rod eye) (Fig. 3.8).

To carry out these tests the rotating steel ring at ambient temperature was suddenly sprayed with ice spray to its inner side several times at a constant circumferential velocity of approx. u=15.8 m/s. The temperature gradient achieved in this way was very small with Δt_{IR} / Δtime = -0.4...-0.5 K/s. However, even this small temperature deviation at the inner surface of the steel ring could be detected by the magnetic field sensor with a small time delay of only about 4... 5 s.

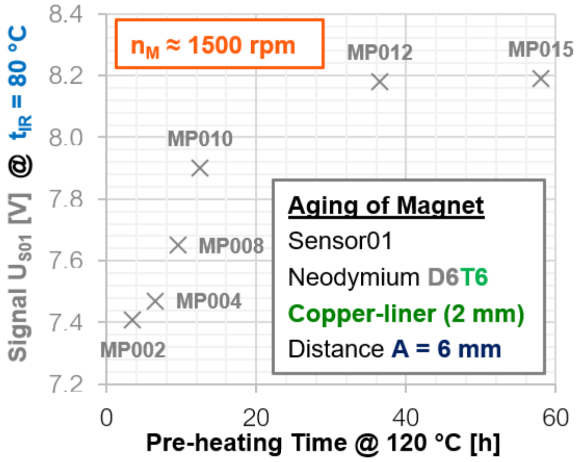

Figure 3.9. Thermal long-therm influences

To consider the influence of magnets aging due to heating to temperatures above 100 °C, the cooling tests were repeated under constant boundary conditions until the sensor signal U_{S01} delivered almost identical values at the same reference temperature t_{IR}. In a comparison of the sensor signals U_{S01} at a reference temperature t_{IR} = 80 °C, the same voltage could be determined after an aging time of 36.5 h as after 58 h.

To illustrate the end of the thermal aging of the neodymium magnet, the resulting sensor signals U_{S01} were diagrammed again at a reference temperature t_{IR} = 80 °C versus the residence time during furnace aging (Fig. 3.9). All values diagrammed were recorded at the speed n_M ≈ 1500 rpm, corresponding to a circumferential speed u = 15.7 m/s. After about 37 hours in the furnace at temperatures of about 120 °C, the magnet had reached the stable behaviour with constant magnetic field-strength. The cooling tests with Sensor01 could be finished. The useful signal was reduced by about 17 % because of thermal aging (sensor signal 12 V without magnetic field / negative characteristic curve).

4 EXPERIMENTS AT TEST-ENGINE

After satisfactory completion of the experiments with the model structures, corresponding tests were prepared and carried out on a real Diesel engine. Due to the ownership of the FM16/24 "Norbert" single-cylinder research-engine at that time, originally intended for this purpose, the older single-cylinder engine SKL 1VD18/16-AL "Rudolf" (180 mm stroke, 160 mm bore, output 75 kW @ 1500 rpm, common-rail fuel injection system) was used for this purpose, despite the considerably limited installation space.

Because of the further development work for the special new sensor and its controller system these experiments began in the same setup as with the commercially available Sensor01, as used for the model tests.

4.1 Engine Tests with Fixed Mounted Magnets

First tests at a large single-cylinder engine with magnets, fixed mounted and heated by the cylinder liner should demonstrate the influence of conditions inside crankcase to the sensor system (Fig. 4.1). By using fixed magnets possible problems of dynamic measurements with high sample rates were excluded at first.

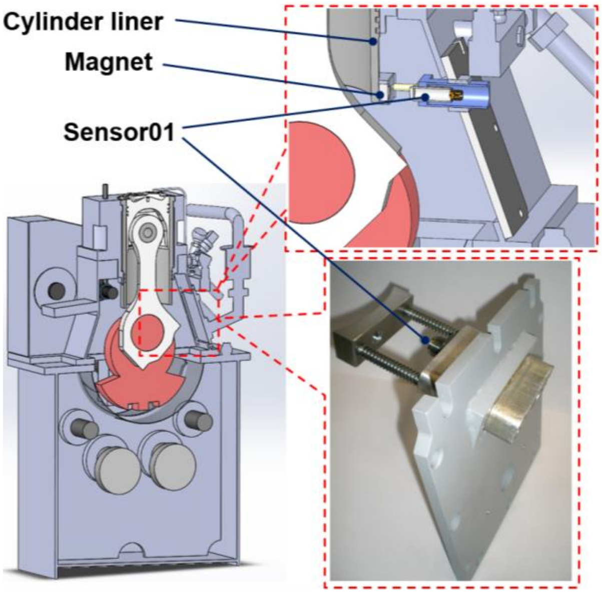

Figure 4.1. Experiments for the influence of crankcase atmosphere

With this setup the behaviour of the measurement principle during several pre-heating procedures was analysed. Therefore, the engine was pre-heated with a lube-oil pressure of 1 bar at the beginning. After a reaching a lube-oil temperature before engine of 65 °C, the lube-oil pressure was enlarged to 4 bar, resulting in a temperature step inside the crankcase (Fig. 4.2). Temperature t_{LB} of the cylinder liner responds immediately.

Remarkable was in these cases, that the sensor signal U_{S01} was able to detect the large temperature steps in every case but failed while smaller temperature gradients. Especially after the switch to 4 bar oil pressure sensor signals did not track the real temperatures. Even tendencies were detected wrong in every case.

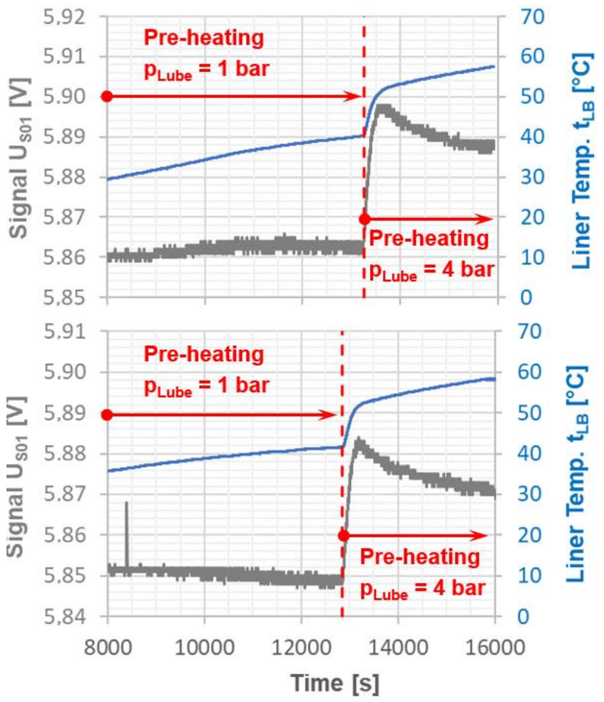

Figure 4.2. Experiments for the influence of crankcase atmosphere

With extensive considerations regarding the influence of oil-mist atmosphere, ferromagnetic influences and possible relative movements the heat transfer to sensor was finally recognised as the explicit reason.

The influence of the temperature at this sensor type at site inside the crankcase was nearly at the same level as the usable signal deviation resulting by the enlarged temperature.

Constructive solution was a sensor mounting frame, cooled by compressed air. For this reason, magnetic field sensor was covered by a thermal isolating housing, made of synthetic material. Integrated cooling channels were flushed by 2 bar air supply, purging the sensors head.

By that way the sensor is never in contact with the atmosphere inside the crankcase. All measures for explosion prevention will not be necessary even for operation with low-flashpoint fuels.

Further engine tests at SKL 1VD18/16-AL “Rudolf” were carried out with that installation to ensure functionality of the sensor system before metal-cutting machining of the con-rod started. Fig. 4.3 shows the results.

After pre-heating with engine start the sensor signal raised immediately correlating with the temperature of the cylinder liner. By on/off-switching the engine cooling of lube-oil and jacket water the temperature of the cylinder liner was rapidly varied. Sensor signal followed with small delay of some seconds, so that the in principle the functionality of the method for crankcase monitoring could be confirmed even under the ambient conditions with lube-oil mist and high temperatures.

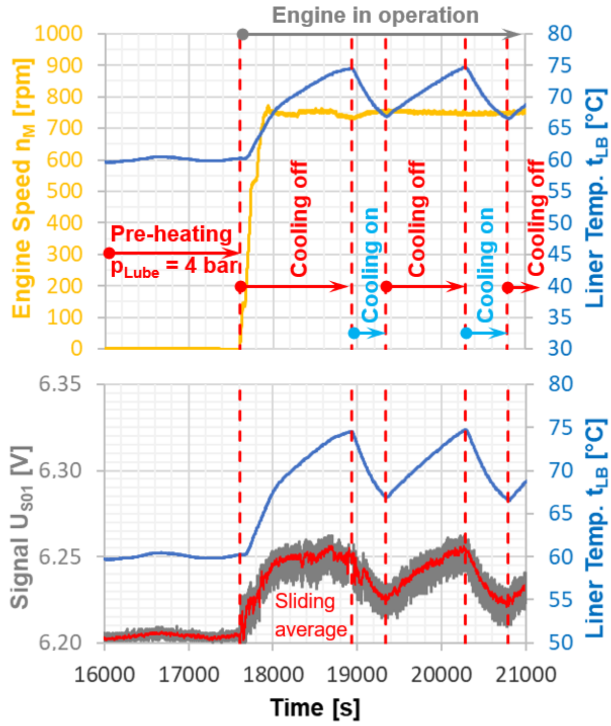

Figure 4.3. Engine tests with cooled sensor

4.2 Engine Tests for Con-rod Bearing Monitoring

Space for installation of sensor, its cover and magnet at the big-end bearing in a line of sight was small (Fig. 4.4). According to Fig. 3.3 the distance L = 6 mm between Sensor01 and the neodymium magnet in the dimension D6T6 was chosen, to ensure high signal level without electric interference from power supply, electronic common-rail fuel system, solenoid valves or electric generator for retarding of the engine. The use of larger magnet diameters was discarded by concerns regarding the necessary hole diameter >10 mm for drilling into con-rods big-end.

The sensor cover was made of oil-resistant synthetic material ABS by rapid prototyping (Fig. 4.5). To reduce the heat convection from crankcase atmosphere directly to the magnet and to enlarge the influence of the bearing shell temperature magnet was covered by synthetic material, too.

Before installing the modified con-rod bearing cover again to the engine the magnetic behavior at the inner surface was tested by iron-particles. No magnetization was found there. This way there was no danger for accumulation of metallic abrasion inside the con-rod bearing and its destroying impact to the inner bearing surface and the crankpin.

For measurements of temperature inside the crankcase t_{TR} an additional temperature probe was installed for reference. As before a galvanic insulation of all test equipment and application of a low-pass filter for sensor's raw signal were necessary. Due to influence of the engine vibrations to the sensor signal U_{S01} the end of searching for minimum during post-processing (refer to Fig. 3.6) had to be raised by 0.1 V.

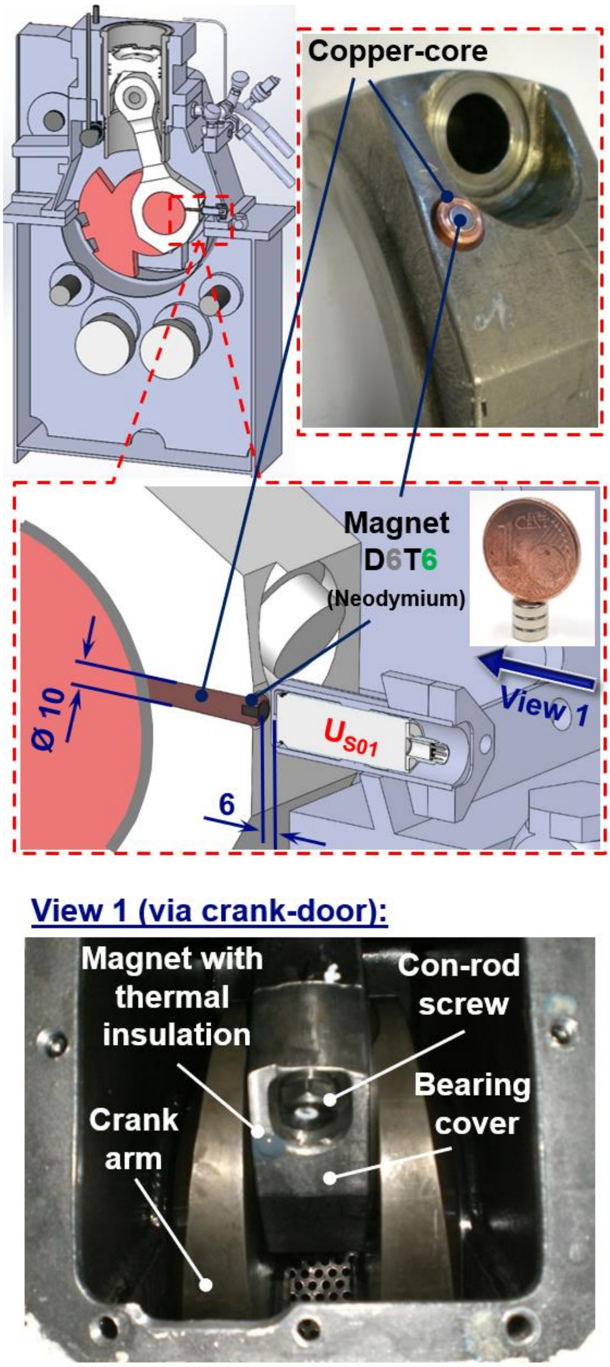

Figure 4.4. Installation of sensor system

Various engine tests had to be carried out in fired and generator-driven operation with speeds of 150 ... 1200 rpm.

Initially, the minimum possible pool temperature in the cooling tower was generated manually over a period of hours with maximum possible re-cooling. In the basin of the cooling-tower less than water temperatures of 13 °C could not be achieved at ambient temperatures of 25 °C. After the usual preheating procedure, the engine was started. The thermostat for lubricating oil cooling was decommissioned. The lube-oil was not re-cooled. When normal lube-oil temperatures of approx. 70 °C and cooling-water temperatures of 80 °C were reached, the measurements were started. The maximum possible cooling-tower volume flow was set by hand to generate maximum possible temperature gradients inside the con-rod bearing.

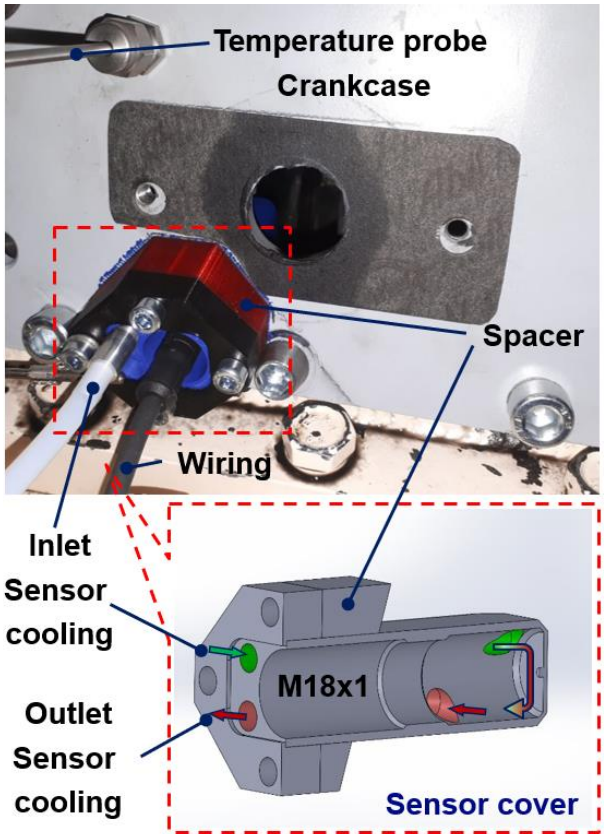

Figure 4.5. Sensor installation at crank-cover

The results are shown in the diagram in Fig. 4.6. The lube-oil temperature at entry of the engine is represented by the brown line. The blue measurement line shows the almost simultaneous arrival of the now cooled oil in the crankcase. The sensor signal U_{S01} was processed by a sliding average of 30 revolutions. Vibrations of the machine necessitated smoothing in the form of a sliding averaging (red).

At the beginning of slide-bearing damages, temperature gradients of 15 K/s at bearing-back are mentioned [17]. But even with the only low temperature gradients possible in the experiments described, the sensor signal U_{S01} followed the changes of lube-oil temperature with a time delay of less than 10 s, which roughly corresponds to the usual switching time of an oil-mist detector for all different measuring points, so that the bearing temperature monitoring and oil-mist detector work on the same time of reaction.

At every operating point, the new measuring principle was able to prove its safe function. However, the required sensor spacing of A = 6 mm was not sufficient for a marketable application, as a competitor's product is declared with sensor distances in the range of A > 30 mm.

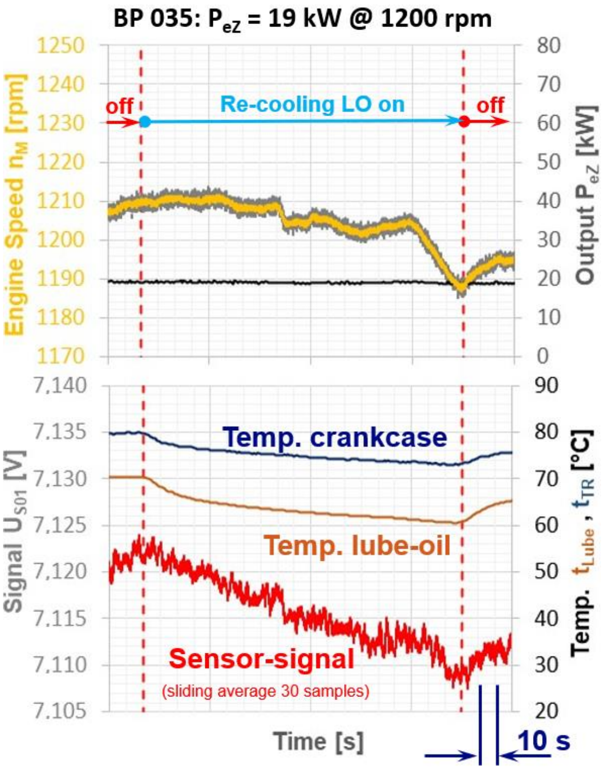

Figure 4.6. Engine tests for con-rod bearing monitoring

There is also room for improvement in the small change of the sensor signals in the range of millivolts, which could makes the system unimmunised against electrical and electromagnetic interferences. Further improvements were urgently needed here. It should be noted that the new system detects only temperature deviations reliably. Due to superimposed interference signals (in particular magnetic ageing and variable sensor distances due to thermal expansion), it is not possible to specify the temperature at the slide-bearing itself directly.

4.3 Development of the sensor system "NORISet"

Time-parallel with the start of experiments with the commercially available Sensor01 the development of special designed sensor types began. Different principles of function were tested. The controller's software was programmed in the same way as used for post-processing operations with Sensor01.

After multiple tests with different sensor types and based on the results regarding sensitivity and the first operating experiences with the Sensor01, a GMR-principle was finally chosen as basic technology for the newly developed sensor generation VM3.1 (Sensor07). The raw signal is additionally amplified internally to analogue output signals with 0 ... 10 V with positive characteristic curve. To achieve the similar dependency of sensor signal from temperature and field strength of the magnets as seen with Sensor01 this output signal of the controller had to be multiplied by (-1).

To adapt to the sensor distance A, a compensation input is available, which can be applied with a maximum voltage of 10 V to prevent overmodulation of the sensor system, possibly at small sensor distances required by design.

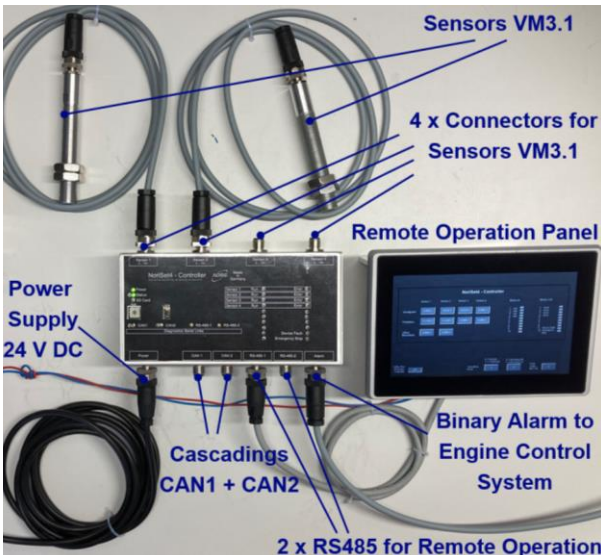

Figure 4.7. Development of the sensor system "NORISet"

The NORISet-controller is equipped with connections for 4 sensors (Fig. 4.7). Cascading of controllers for multi-cylinder engines is possible via two redundant CAN interfaces, so that up to 20 bearing points can be monitored by 5 controllers in that stage of development. Increasing the sensor connections at the controller seems to be preferable to reduce effort of wiring and the system price.

The processing of the sensor's raw signals is identical to the manual post-processing analyses described above. A remote control can be implemented via two RS485 channels. The binary output transmits alarms to the engine safety system.

4.4 Testing of the complete sensor system "NORISet"

The complete sensor system "NORISet" with the sensor generation VM3.1 (Sensor07) was installed in the test engine. Even with the maximum possible compensation voltage of 10 V, the distance between the sensor and the magnet had to be set to at least A = 26 mm to prevent overmodulation. Larger sensor distances were not possible from a structural point of view. The tests were carried out in the same way as those with Sensor01.

In addition to the basic function of the sensors with competitive sensor distances A, the correct implementation of the evaluation strategy inside the controller was also confirmed (Fig. 4.8). Manual post-processing (red) and negated controller signal (purple) run in parallel with low offset. In contrast to the tests with the originally used Sensor01, a reliably evaluable and interference-resistant sensitivity of $\Delta U_{S07}/\Delta t_{Lube}$ = 0.5 V / 10 K could be achieved with this configuration.

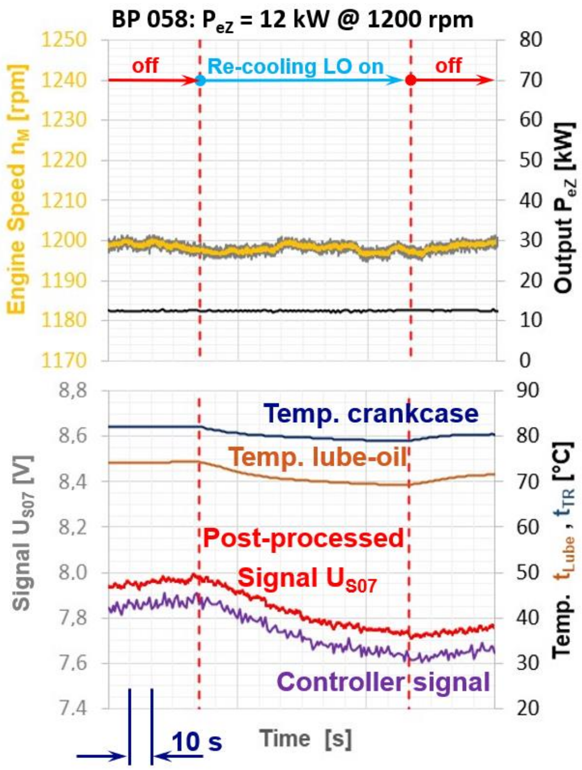

Figure 4.8. Experiments with sensor system prototype "NORISet"

5 CONCLUSIONS

With several experimental investigations the low-level and slow reaction of splash-oil systems for detection of alternating operating conditions inside con-rod bearings were considered. By variations of engine parameters, such as start of fuel-oil delivery, charge-air pressure and charge-air temperature the massive interaction of splash-oil temperatures and piston cooling oil were detected and caused by flow-measurements at pre-heated non-operating engine.

Percentage of lube-oil left con-rods big end was at the test engine FM16/24 "Norbert" less than 3 % of piston cooling oil, so that even with high-sophisticated concepts for collecting devices separation of the flow from con-rod against the other source of lube-oil inside the crankcase, returning from the different points of lubrication, would be improbable.

Beside possible critics regarding the methodology of the splash-oil experiments, carried out in this project (no real bearing damage provoked), it has to be remarked generally, that an up-coming damage at con-rod bearing, occurred by an interrupted oil-supply (e.g twisted main bearing shells) is even in theory not detected by splash-oil systems, as well as there would be no lube-oil splashed off for temperature analysis.

Systems directly measuring temperatures of con-rod bearings based on radar, RFID and surface acoustics are known, but expensive or not deliverable. They often require wiring inside crankcase.

Based on this status, the target for the joint project described became the development of an easy operable, contactless and non-optical monitoring system for the operating conditions of moved bearing shells as well as its functional demonstration while engine operation. Aim of price level for whole system, incl. controllers, CAN-bus and classification was fixed to <1000 €/cyl..

With "NORISet" the functional prototype of a sensor system for the thermal monitoring of moving machine elements was developed. With the methods presented, temperature gradients can be determined non-optically and free of contact. No wiring inside crankcase will be necessary. Moving parts (magnets and their auxiliary devices) at the machine elements monitored are free of power supply. Sensors are mounted in special covers and this way not in contact with the oil-mist atmosphere inside crankcase. No type of protection against explosions seems to be necessary.

Especially for highly loaded Diesel engines onboard seagoing vessels with tight time-schedules (e.g. fast ferries) and large engines (Diesel, gas) in stationary power plants operating in isolated networks (e.g. power generation at islands or for nickel mines) this sensor system is predestined for operation.

The application is not only restricted to con-rod bearings and crossheads inside large Diesel and gas engines. The monitoring of large compressors for natural gases or torsional vibration dampers is also being considered. It is possible to retrofit engines and machines in the existing fleet and land-based field.

Compared to competitors' systems the only disadvantage of "NORISet" is the impossibility of measuring real temperatures, but only temperature deviations, what is sufficient for monitoring of correct operation or detection of damages, coming up. Reliable detection for the sensors used are demonstrated at sensor distances above 26 mm. At this level of development, the price for complete system with 8 sensors and 2 controllers for 8L engine was calculated to 956 € / cyl. including classification, what seems to be very attractive for directly measuring con-rod bearing monitoring system. Systems' price could be reduced by further steps of development (e.g. multi-channel controllers).

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