Technical Paper

Condition Monitoring of Construction Machinery Power Train Using Oil Contamination Concentration Sensor

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Extension of overhaul intervals is being eyed primarily for large-sized mining machinery to reduce maintenance cost. With this increasing trend, power train components including reduction gears are likely to be operated for longer duration. As they are operated longer, components are likely put at greater risk of breakage, making maintenance more important than ever. Programs have been pursued to develop an oil contamination concentration sensor and a related monitoring system using the sensor to help prevent breakage through monitoring of routine maintenance and enable early detection of abnormalities to contain damage and reduce downtime. The new monitoring system enables abnormalities that may occur on vehicles operating at remote sites to be detected.

Key Words: *Condition monitoring, Reduction gear, Lubricating oil, Sensing*

1. Introduction

Construction machinery's power train components (**Fig. 1**) internally have many sliding. With the accumulation of operating hours, sliding is subjected to material wear and fatigue, and eventually break. With large-sized mining machinery, a combination of proper maintenance to maximize long term service life and periodic overhaul has realized extended operation exceeding 50,000 hours.

Fig. 1 Construction machinery components

In recent years, overhaul sessions tend to be farther apart to reduce maintenance cost and maintenance downtime. As a result, components tend to be operated longer until the next overhaul. As components operate longer hours between overhauls, maintenance is more important than ever, and so is minimizing damage from abnormalities that may occur. In addition, while extending overhaul intervals can be considered an improvement within the framework of time-based maintenance, that trend can possibly transition to condition monitoring-based maintenance for the sake of cost optimization. Along with those moves, it is increasingly becoming important to monitor the condition of components and the status of maintenance. On the other hand, for mechanics in charge of maintenance, it is difficult to directly and frequently observe the condition of construction machinery that is often operating in remote areas.

To accommodate the circumstances, programs are underway to develop technology to remotely monitor the condition and maintenance status of power train components. As part of efforts toward achieving condition monitoring especially of power train components including transmission and axle, this paper discusses the development of an oil contamination concentration sensor that measures the concentration of contaminants in lubricating oil and the creation of a condition monitoring system using the sensor.

2. Reduction gear abnormality detection

On construction machinery, many of power train components use reduction gear boxes. Reduction gear parts such as gears and bearings are subjected to fatigue and wear as they run in the working machine. Those parts typically transition from initial wear which occurs with a higher wear rate in the early machine working hours to normal wear with a steady low wear rate to abnormal wear, ending with breakage (**Fig. 2**). By maximizing the normal wear period through proper maintenance and enabling to detect symptoms of breakage-inducing abnormalities early, it is considered possible to extend overhaul intervals without having severe breakage or machine breakdown. For reduction gears, various abnormality detection methods have been proposed that are based on vibration, AE, temperature and other parameters [1]. At Komatsu, efforts were launched to develop abnormality detection technology focusing on change in the concentration of contamination, primarily wear dust, in lubricating oil. The oil contamination concentration-based abnormality detection method is thought to be capable of not only detecting abnormal wear of gears and bearings but also of monitoring the maintenance state of lubricating oil which influences the service life of gears and bearings.

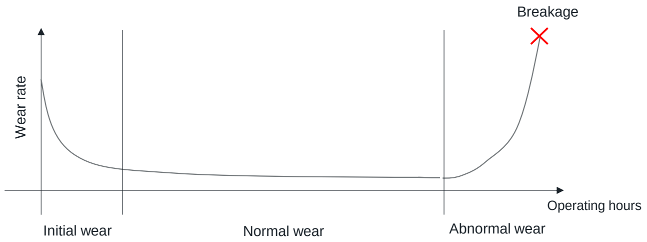

Fig. 2 Wear curve

3. Oil contamination concentration sensor

3.1 Lubricating oil condition monitoring through oil analysis

For condition monitoring of lubricating oil, oil analysis service has been used whereby oil samples from the machine are analyzed for wear dust, the amount of foreign material and the extent of degradation. The results of oil analysis (**Fig. 3**) on a reduction gear which broke at 11,000 operating hours show a steep increase in the concentration of iron dust in the oil prior to the failure. Oil analysis service has proven reliable not only in early abnormal detection, such as in the case cited in **Fig. 3**, but also in locating and identifying the cause of abnormalities.

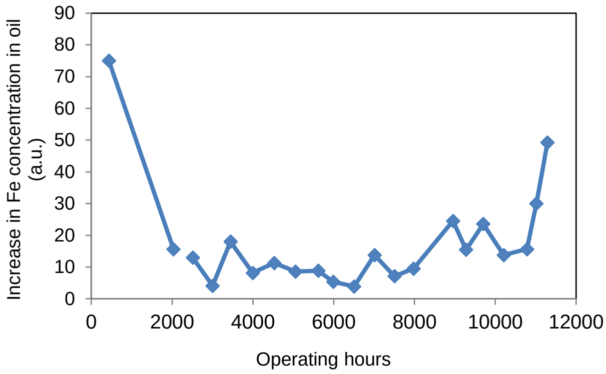

Fig. 3 Change in iron concentration increase in reduction gear lubricating oil

Oil analysis service thus far conducted has shown that many of abnormalities found in reduction gear lubricating oil relate to high concentrations of iron and sand (**Fig. 4**: Example of axle oil abnormalities). This means that most of abnormalities identified in lubricating oil monitoring relate to abnormal wear of internal parts and the ingress of earth and sand due to poor sealing. Abnormalities found other than earth, sand and iron include water ingress and a rise in copper concentration in oil due to abnormal wear of clutch facings.

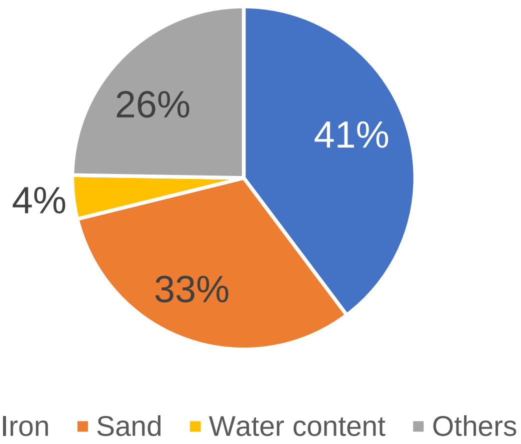

Fig. 4 Breakdown of abnormalities found in axle oil analysis

3.2 Development of on-board oil contamination concentration sensor

While proven reliable, oil analysis-based condition monitoring has presented a number of issues including limited opportunities for oil sampling and analysis, time lag between oil sampling and results and inaccurate oil analysis resulting from inappropriate sampling process. Out of a desire to resolve those issues, attempts were initiated to develop an on-board oil contamination concentration sensor capable of measuring oil contamination online.

(1) Measuring method

A number of sensing methods have been proposed, such as those based on inductance balance and permittivity, for lubricating oil properties including contamination concentration. Different measuring methods have different limitations in terms of measurable items and installability (**Table 1**). As an example of those limitations, particle counters can only function in fluids running in piping with certain flow rates. Methods for reduction gear lubricating oil of construction machinery must not only be capable of measuring iron-bearing wear dust, a typical issue with reduction gear lubricating oil, but also can be installed easily on an oil bath-lubricated setup. Accordingly, a method using transmitted light was chosen for the sensor.

Table. 1 Lubricating oil sensing methods

Measuring method	Measured item: Foreign material (solid) – Ferrous	Foreign material (solid) – Non-ferrous	Cleanliness	Water content	Degradation – Oxidation	Degradation – Additive agent	Installability
Permittivity/ Electric conductivity	×	×	×	○	○	○	Good
Inductance balance	○	×	×	×	×	×	Only piping
Magnetic switch	△	×	×	×	×	×	Good
Transmitted light	○	○	×	△	×	×	Good
Particle counter	×	×	○	×	×	×	Only piping

○	Good
△	Measurable
×	Not measurable

The sensor's measuring unit essentially consists of an LED and a photodiode (photodetector), which measures the intensity of light transmitted through the oil (**Fig. 5**). Light is scattered as it is transmitted through contaminated oil and, as a result, the light reaches the photodetector with reduced intensity. The more contaminated the oil, the weaker the intensity of the detected light. Among optical measuring equipment available, laser diffraction particle size distribution analyzers and high-performance turbidity meters are capable of measuring the intensity of scattered light by each scattered angle, offering particle size distribution of foreign material and various other measurements. With construction machinery, measurement targets for condition monitoring sensors are narrowed down to just transmitted light due to cost and size constraints. The scattering cross section per unit weight of the contaminant varies depending on the type and size of the contaminant. Therefore, when the concentration of the contaminant in the oil is to be estimated based only on the transmitted light, the type and particle size of the contaminant has to be assumed.

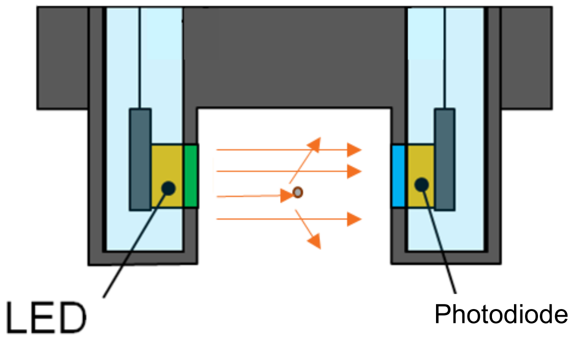

Fig. 5 Measuring unit of the oil contamination concentration sensor

The sensor's measurement accuracy was investigated using oil that had been used in reduction gears of construction machinery. The results of the accuracy investigation agreed well with the corresponding measurements from an ICP-OES, which is widely used in the analysis of element concentration in oil (**Fig. 6**). Theoretically, the relationship between contaminant concentration and transmitted light intensity changes depending on the contaminant's particle size and other parameters. Therefore, the agreement appears to be due to the particle size distribution of the iron-bearing wear dust in the oil being uniform.

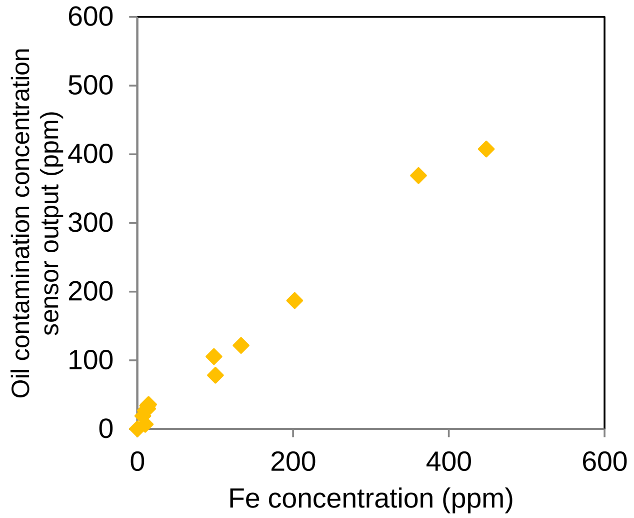

Fig. 6 Measurement performance of the oil contamination concentration sensor

(2) Power source, shape

On construction machinery, reduction gears are sometimes located where they are likely hit by earth, sand and other obstacles and/or are sometimes a rotation body. Therefore, routing the wiring to a sensor on a reduction gear in those locations often raises related challenges. To make itself installable even on those locations, the sensor utilizes the Seebeck effect (**Fig. 7**) to self-generate power, and the measurement data is transmitted wirelessly, in combination resulting in eliminating the need for wiring to the sensor. The KELGEN SD [2] from KELK, with whom the sensor was developed, offered the original technologies to realize the sensor's self-generation of electricity and wireless data transmission. Shaped like a bolt (**Fig. 8**), the sensor can simply be screwed into any existing port with the same thread diameter and other dimensions to start measurement.

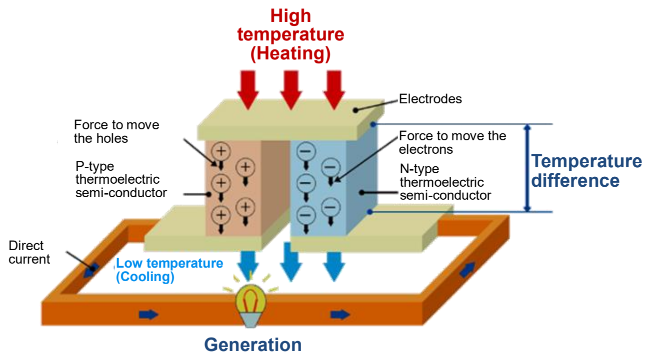

Fig. 7 Seebeck effect

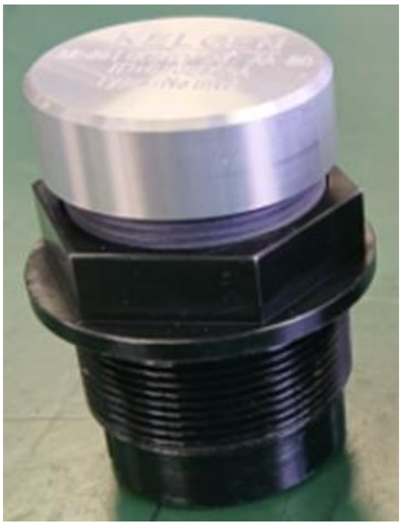

Fig. 8 Oil contamination concentration sensor

4. Condition monitoring using oil contamination concentration sensor

This section of this paper presents some of applications and operational systems of construction machinery condition monitoring using the oil contamination concentration sensor.

4.1 Installation of the oil contamination concentration sensor

The following is an example of the hardware configuration, required on the machine, for the condition monitoring system using the oil contamination concentration sensor. The machine in the following example is a dump truck. With a dump truck, lubricating oil in the transmission and axles is measured for contamination. A sensor is installed on each reduction gear. Measured data is transmitted wirelessly from the sensor to a receiver installed on the machine frame. From the receiver, the data is sent to the controller in the cab. The sensor is an optical sensor, whose measurements are affected by bubbles in the oil. To obtain valid data, care must be taken to collect unaffected measurements, such as by installing the sensor in bubble-free locations and collecting data only after bubbles have dissipated.

4.2 Monitoring system

Data from the sensor that has been accumulated in the on-board controller is regularly transmitted together with the machine's operation data via satellites or other means to the cloud server for processing and report generation (**Fig. 9**). When any abnormal trend is detected in the contamination concentration being monitored, the mechanic in charge at the distributor will be alerted on the trend and given advice on maintenance and preventive actions required on the machine to prevent severe breakage and minimize downtime.

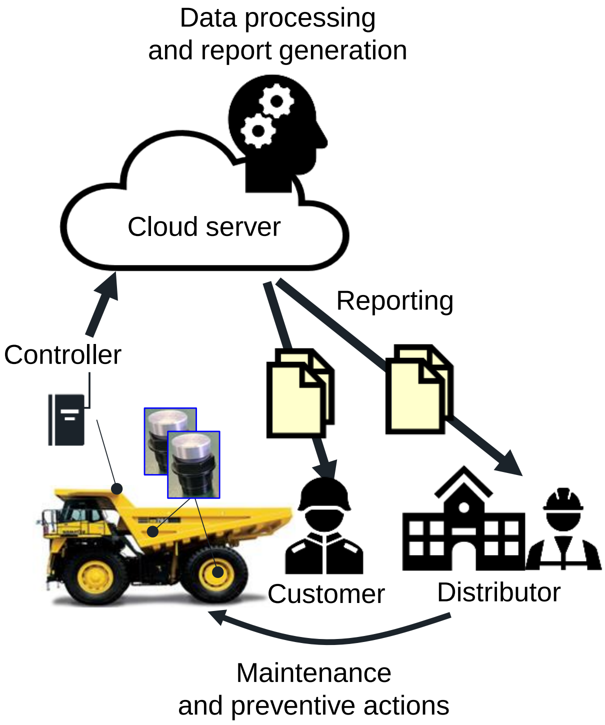

Fig. 9 Monitoring system

In normal operation, the reporting screen provides access to the maintenance status by offering the trend in oil contamination concentration, oil replacement record based on the contamination concentration trend, the latest operating hours of the oil and other related information. The visualization scheme is intended to help prevent maintenance omission and facilitate swift actions in the event of a sudden failure, to prevent serious machine issues.

4.3 Applications of the oil contamination concentration monitoring

Here are some examples of abnormalities detected during the condition monitoring using the oil contamination concentration sensor. The condition monitoring has proven effective not only in early detection of reduction gear breakage but also in identifying maintenance process defects and detecting the ingress of foreign material, starting to be recognized as a contributor to failure prevention.

(1) Flushing process defect

On a machine on which lubricating oil cleanliness is improved regularly by carrying out flushing using the offline filter, the sensor was found to show higher output values after flushing where lower outputs are the norm after the process. Investigation found that the flushing process was to blame, leading to early corrective actions. This shows that the monitoring using the oil contamination concentration sensor is effective not only for reduction gear failures but also for defects in lubricating oil maintenance including oil replacement and flushing.

(2) Water ingress

The oil contamination concentration sensor showed abnormal output values, which led to a diagnosis of water ingress in the lubricating oil for the traveling reduction gear and early remedial actions. While the basic experiment found that the sensor is capable of measuring the concentration of iron-bearing wear dust only, it actually was able to detect the ingress of more than a certain amount of water, which is as a result of the lubricating oil emulsifying and becoming less transparent from reaction with the water (**Fig. 10**). Continuing to run a reduction gear lubricated with water-contaminated oil can cause the internal parts to rust and break. Therefore, it is important that water ingress be detected early to prevent breakage.

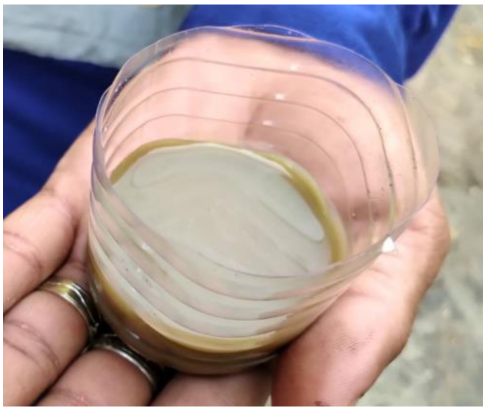

Fig. 10 Emulsified oil from water ingress

5. Conclusion

A condition monitoring system for reduction gears using an oil contamination concentration sensor is presented in this paper as a means to meet the growing demand for the visualization of maintenance status to accompany extended overhaul intervals for maintenance cost reduction and for early detection of abnormalities. Machine condition monitoring is a must-have technology for reasons including the possible need to have something to detect unusual noise and other abnormalities, that are currently typically found by operators, when in the future construction machinery becomes autonomous, unmanned units. It is hoped that the oil contamination concentration monitoring sensor can be a step toward machine operational cost optimization and realizing autonomous, unmanned machines.

References
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Introduction of the author

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[A comment from the author]

We will continue to contribute to the reduction of maintenance cost and the streamlining of maintenance operation of machines by offering condition monitoring solutions such as the oil contamination concentration sensor presented in this paper.