Wear detection by monitoring hydraulic oil contamination – an experimental comparison between on-line and off-line measurements

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Abstract: An experimental rig was set up to provoke accelerated wear of spherical roller thrust bearings. Wear detection was evaluated using both an on-line light-blockage type particle counter and off-line samples for Laser Net Fines particle counting and oil condition analyses. Online particle counting showed a steady state behavior throughout most of the test and an exponential increase in cumulative particle detection toward the end of the test. At this point, significant wear was found on the rolling bodies of the bearings. Off-line sampling showed no clear trends identifiable in the particle levels. This is believed to be related to sampling issues and highlights the sensitivity of off-line measurements. The exponential increase in the on-line particle detection was successfully identified by an alarm algorithm, showing the potential for automatic wear detection.

1. Introduction

Condition monitoring of hydraulic systems is a way to ensure good operating conditions, long service lifetime and minimal losses in terms of unexpected functional failures. Continuous monitoring of oil condition is made possible by sensor technology miniaturization and cost reduction. By continuous monitoring, the capacity for detecting trends and abnormal system behavior is dramatically improved. However, off-line sampling also has advantages in that a single sample can be analyzed by an array of analysis equipment extracting much more information about the system state. This equipment is in most cases also superior in accuracy and reliability when compared to the sensors used for continuous monitoring.

In this study early detection of wear by use of on-line and off-line particle counting is evaluated experimentally. Focus is on low-speed, high torque applications, an area in need of more research. Abnormal wear near end of component life is typically characterized by an accelerating generation of wear particles. For a detailed review of wear and fatigue in rolling contacts, see [1]. While wear of components in itself is an issue, it becomes all the more important since the generation and distribution of wear particles in e.g. a hydraulic motor can be a root cause for catastrophic seizure brought on by trapping of particles in clearances between moving parts [2].

In a comparison of different monitoring techniques, both optical (off-line) and inductive (on-line) particle counting has been found to provide early detection of bearing wear [3]. Dempsey et al. have successfully shown the capability of wear detection using inductive particle counting in both bearing and gear setups [4-7]. The cumulative mass of detected debris was found to be a good indicator of abnormal wear. This was also the finding of Miller [8]. Isaksson [9] successfully used a combination of optical particle counting and artificial neural networks to generate early warnings of abnormal bearing wear.

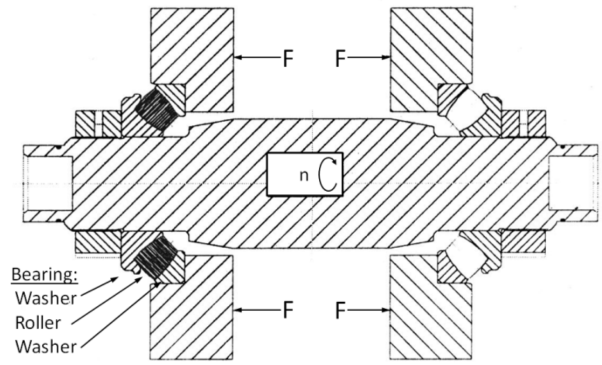

Figure 1: Schematic drawing of the bearing wear rig, taken from [10].

2. Experimental Setup

2.1. The test rig

The experimental test rig consists of a modified Hägglunds hydraulic motor constructed primarily to perform fatigue testing on spherical roller thrust bearings [10]. Bearing wear is provoked by running the rig with high bearing loads at low rotational speeds, 6-8 rpm. The central motor house transfers the hydraulic pressure to axial load – F – on the bearings while an external motor provides rotational motion – n – of the central shaft, se Figure 1. A more detailed description of the test rig can be found in [10]. The bearing houses are flushed with lubricating oil which is then analyzed at the drainage point. The drainage circuit incorporates an on-line particle counter as well as an oil sampling unit and a magnetic chip detector placed just prior to the system return filter.

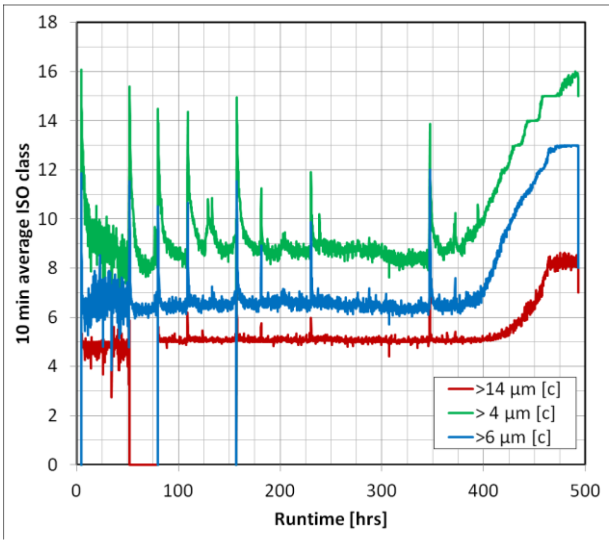

Figure 2: ISO class output from the particle counter. Values averaged every 10 minutes.

2.2. On-line monitoring

Oil contamination is monitored on-line by a light blockage type particle detector which outputs the ISO4406:99 contamination levels for the oil. The data is continuously evaluated by a Condition Monitoring Unit capable of sending remote warnings and of interrupting the test in case of excessive levels of contamination.

2.3. Off-line monitoring

Oil samples are taken at intervals of 24 hrs using a pressurized on-line oil sampling unit which ensures that samples are representative of the oil condition. Off-line samples are analyzed in the ITH Analysis lab where particle counting is performed with a Laser Net Fines (LNF) instrument which provides particle count along with image analysis of contamination particles. The image analysis is capable of classifying contaminants based on their size and shape, separating particles into categories such as "*Cutting*", "*Severe Sliding*" and "*Fatigue*" wear, as well as non-wear particles (water droplets, air bubbles).

3. Results

3.1. On-line monitoring

The on-line monitoring results are shown in Figure 2. During the first half of the test, a series of adjustments were made to the setup which required stopping and starting. After each restart of the system, the on-line monitor displayed a peak in reported contamination levels. The value then proceeded to stabilize at a considerably lower level. The possible origin of these peaks is discussed below. After ~400 hrs running time, the particle levels began increasing significantly which prompted test stop and inspection at 500 hrs. At this point significant wear of the bearings was identified. The magnetic chip detector displayed only a "sooty" look at this point and no clear accumulation of magnetic debris.

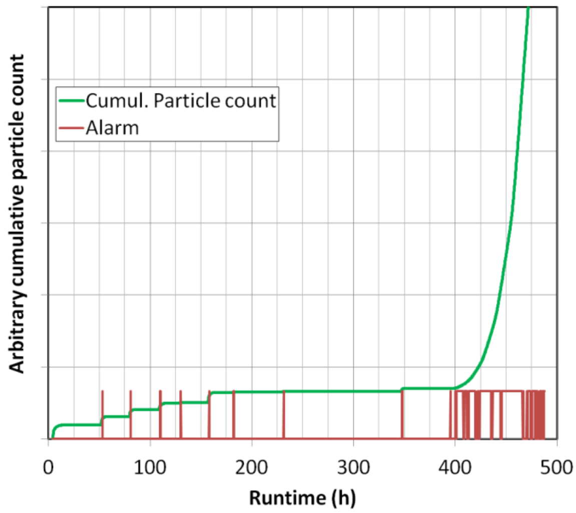

Figure 3: Cumulative on-line particle count showing triggered alarms at the onset of abnormal wear. False alarms issued at at start/stop of the system.

The output data was then pre-processed and presented in the form of "arbitrary cumulative wear" which resulted in a smoother appearance of the contamination level in the system (Figure 3). At around 400 hrs runtime, the measured contamination levels increase exponentially, indicating abnormal wear. Using a previously developed warning algorithm [11], the exponential increase could be automatically identified by the system at t = 395 hrs resulting in an alarm. There is an issue with false alarms generated by the algorithm, particularly when starting/stopping of the system. This will be addressed in a coming research paper.

3.2. Off-line sampling

3.2.1 Particle counting

The results of LNF particle counting on off-line samples were much more difficult to interpret, see Figure 4. Generally, higher levels were found in the off-line samples than the on-line counter presented. Furthermore, elevated levels during the tests first ~200 hrs made trend detection in contamination levels difficult. Identification of an abnormal wear situation at 400+ hrs is obscured by the elevated levels earlier on. Finally, even as the abnormal wear situation indicated by on-line monitoring progresses until test stop, the final off-line sample shows a reduced level of particle contamination.

Taking into account the wear particle classification, the same confounding trend with higher levels during 0-200 hrs is found. The origin of such misleading results is discussed below.

3.2.2 FTIR analysis

FTIR analysis is a tool used in order to evaluate oil ageing. The results comparing two FTIR spectra are shown in Figure 5. No discernible change could be found in the oil condition between 100 hrs and 494 hrs. This is expected since the running time of the test is quite short and oil ageing during this time is not to be expected.

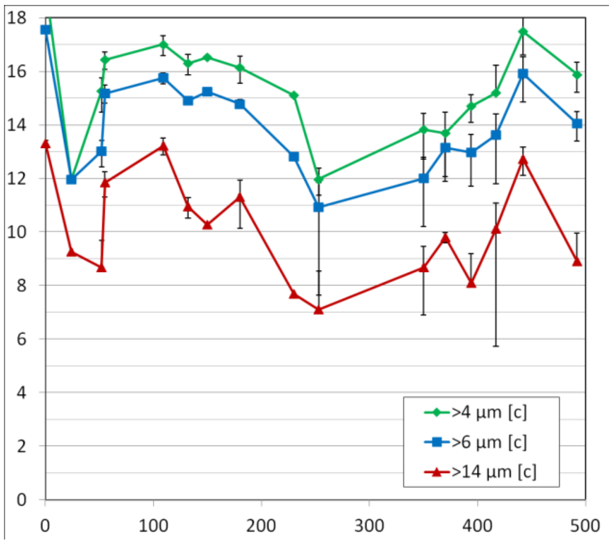

Figure 4: ISO levels as determined by off-line LNF particle counting.

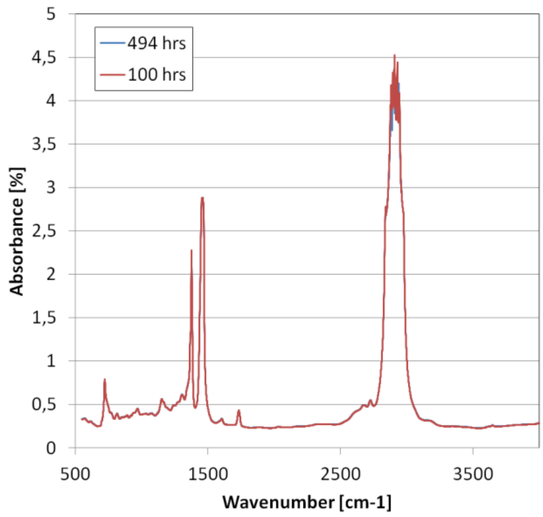

Figure 5: FTIR spectra from samples taken at 100 hrs running time and 494 hrs running time (test stop).

4. Discussion

The on-line particle levels showed a stable wear situation for the most part of the test with a clearly identifiable exponential increase toward the end. This is expected to indicate that the bearings have entered an abnormal wear state [1]. Peaks in the raw data generated during re-starting of the system can originate from a number of factors. Flow surges are known to dislodge trapped or resting particles in hydraulic systems [12]. At system start the oil flow increases rapidly which may cause this effect and result in the declining peaks seen in the particle count data. Another effect is oversaturation of air or water in the system causing air/water bubbles to circulate in the oil. Such bubbles are indistinguishable from solid particles for a light blocking type particle counter of the type used here. LNF particle counters, such as the one used for off-line analysis, can identify air/water bubbles and ignore them when estimating particulate contamination. As a part of coming work we will focus partly on improved pre-processing and signal processing to eliminate alarms that issue from these effects.

Particle levels found by LNF particle counting on off-line samples did not exhibit the same stable wear situation during the first 400 hrs of the test. Instead, elevated levels were found for the first 200 hrs. These elevated levels make it difficult to confidently identify an increasing trend above 400 hrs. One issue that arises with off-line samples relates to sample size, particularly for low levels of particle count. A very small volume (<10 ml required for LNF count) of fluid is taken to establish a value representative of the entire system. However, although this may cause an uncertainty of +/-1 ISO class, it does not explain the results found.

We note that the high levels of off-line particle count coincide well with the period of testing which involved some stopping and starting. During this period, off-line samples were taken right before test stop, i.e. when the lowest and most stable particle count was reported by the on-line counter. The only hypothesis so far is that some systematic issue with the off-line oil sampler results in accumulation of particles during re-starting of the system and that the sample taken reflects not the momentary level of contamination but a value colored by the preceding test period. This hypothesis would also support the theory of dislodging resting particles at the flow surge caused by system starting. If the peaks found during restart were due to air/water bubbles, we would not expect a relation between off-line sample particle levels and re-starting of the system.

Regarding other off-line analyses we have found that FTIR is not a likely method to use for finding wear trends. We note that this is mainly due to the accelerated nature of the test where wear is reached relatively “fast” – i.e. within a time period that does not involve significant degradation or ageing of the oil.

It must also be noted that due to constraints on time and personnel, sampling was not possible each 24 hrs which explains the longer intervals between some samples.

There are several advantages of using the on-line approach. Most prominent is the continuous and automatic monitoring and evaluation of oil condition. Degradation and wear can be immediately detected and warnings are provided to the operator of the machine who can quickly decide upon which action to take. Both instrument and data treatment devices have small form factor and relatively low cost. The disadvantages are the bluntness of the measurement – ISO level instead of actual particle count – and the risk of false alarms which needs to be addressed by data processing. Regarding the accuracy of the measurement, it has been noted by others that *correct* absolute values of particle contamination is not of great importance when evaluating the wear trend [13]. In other words, the *stability* of the steady-state on-line measurement is of more importance than its agreement with a “perfect” measure of particle concentration when detecting trends that indicate changes in the system wear situation.

Off-line oil analysis is powerful in that it can provide a more complete picture of the oil condition rather than focusing only on the level of particulate contamination. With information on particle types, additive consumption and breakdown as well as elemental distribution of contaminants a more well-informed decision can be made on the status of the motor. However, it comes at a greater economic cost, both in terms of the instruments used and the man-hours required for analysis. It is also likely that the response time for a maintenance decision is considerably longer when relying on off-line analyses.

As this work continues, we aim to incorporate and evaluate several other off-line measurement techniques. Sweep voltammetry, or RULER®, could be an interesting technique when predicting wear since it may provide the possibility of tracking the consumption of anti-wear additives. We believe that ICP elemental analysis also could provide early indications of wear by tracking the level of Fe contamination in the oil.

5. Conclusions

A comparison was made between off-line and on-line particle counting as a means of detecting an abnormal wear situation in a hydraulic system. On-line particle counting provided an early indication of wear, identifiable by an exponential increase in the cumulated wear particle detection. A detection algorithm was used to generate automatic alarms when the system entered abnormal wear. Off-line samples did not exhibit the same clear trend. While this is believed to be related partly to the sampling method, it does illustrate how much the values obtained by off-line analysis are dependent on handling of the oil sample, particularly for low levels of contamination.

6. Acknowledgements

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