

OILPAS - Online Imaging of Liquid-Particle-Suspensions - How to Prevent a Sudden Engine Breakdown

2010-01-1528

Published
05/05/2010

Lars Schomann, Gerhard Matz and Nils Röbbken
Hamburg Univ. of Technology

Sven Krause
Univ. of Kassel

Copyright © 2010 SAE International

ABSTRACT

Amount and size distribution of wear particles in engine lubricating oil are indicators of the current machine condition. A change in size distribution, especially a rise in the amount of larger particles, often indicates a starting wear of some machine parts. Monitoring wear particles contained in lubricating oil during normal machine operation can help to identify the need for maintenance and more important to prevent sudden failure of the machine.

An optical method is used to image a thin layer of oil to count and classify contained particles. Therefore, a continuous flow of undiluted oil from the oil circuit of the machine is pumped through the measurement instrument. Inside the instrument, the oil flow is directed through a thin transparent flow cell. Images are taken using a bright LED flashlight source, a magnification lens, and a digital camera. Algorithms have been developed to process and analyze the images. They are capable of compensating for variations in background brightness, of differentiating solid particles from non-solid particles (such as e.g. air bubbles), of classifying particles and air bubbles by size and shape. Additionally the class growth rate is monitored and classified by a prediction software unit, which is able to identify critical situations.

The image analysis algorithms were trained with different oil samples from engines with varying damages. A differentiation between the causes of damage on the basis of the calculated particle properties was shown. Furthermore the system was successfully tested in various applications at engine test stands. It was capable of indicating an upcoming

crankshaft bearing damage during a short test run. Using gas bubble count and size distribution, a value for the dispersed gas concentration could be calculated, which shows a good correlation with dynamic engine behavior.

INTRODUCTION

Testing complex tribological systems such as modern combustion engines or power trains sometimes yields the risk of unforeseen and sudden breakdown caused by excessive wear, especially if prototype components are employed or pushing the system to the wear limit is desired. If the test is not stopped in time, the result can be the total loss of precious prototypes or measurement data, and often the cause of failure cannot be accurately identified anymore. Therefore monitoring system wear condition during the test is often crucial [1]. Some measurement data typically sampled in real time, such as e.g. drag torque, pressures or temperatures, can indicate an upcoming failure, but they do not represent the actual wear condition.

A more reliable way to determine system wear condition is to analyze wear particles contained in lubricating oil. Most prevalent is analyzing an oil sample in the laboratory, which is drawn from an access point in the oil circuit while the system under test is stopped. Various methods such as microscopy or ferrography can be used to determine particle amount, size distribution and shape, particle properties which are all very dependent on the wear process and degree of wear [2]. Due to other influencing factors such as total oil volume, oil filter performance or running-in characteristics of the system, the total amount of wear particles in one oil sample can vary in a wide range, even for systems with no

eminent wear. In most cases, the size distribution will show a predominate percentage of small particles with a diameter of a few microns. A significant number of larger particles often indicate a starting or even advanced wear of some machine parts. Classifying wear particles by shape helps to determine the predominant wear process, because there are typical particle shapes generated by different wear processes [2].

Even though the analysis of a single oil sample can yield a lot of information, in most cases only trending results enable the user to decide on further test proceedings. Thereby some disadvantages of oil sampling and laboratory analysis become apparent. Any analysis results can only be as good as the sample used, which has to be representative of the oil in the system. If the machine and thus the oil circuit need to be shut down to draw an oil sample, most likely larger particles will settle at the bottom of the system. Procedures have to be generated and followed to guarantee obtaining a representative oil sample and to maintain it until analysis, because any irregularities can easily lead to erroneous trending results. Furthermore frequent sampling to achieve adequate time resolution can disturb the test procedure unduly, and since in most cases the sample volume drawn is lost to the oil circuit, fresh oil needs to be refilled. This in turn leads to a dilution of the wear particle concentration in the oil circuit and can make the detection of only a few wear particles generated by a starting wear on some machine parts more difficult [3].

The OILPAS method described in this study was developed to measure wear particle amount, size distribution and shape in real time while avoiding the problems associated with frequent oil sampling [3]. It is not intended to replace thorough wear particle analysis in the laboratory. The aim is to get time resolved trending measurement results which assist the user to determine the system wear condition at any given time and to avoid fatal system breakdown, while at the same time the oil circuit and the test procedure are disturbed in almost no way.

INSTRUMENTATION

PRINCIPAL OF OPERATION

(See [Fig. 1](#) after last section of paper.)

[Fig 1](#) shows a simplified schematic of the OILPAS method. A thin layer of undiluted lubricating oil passes through the flow cell. An image of the particles contained in that thin layer is projected onto a CCD sensor array by means of a LED flashlight and a magnification lens. The oil flow in the flow cell is not halted for each image acquisition, but the combination of the flow rate and the flash duration is adjusted so that motion blurring of particles is avoided. Each image is transferred to a computer and analyzed using specifically developed image processing and analysis algorithms. Particle

regions in each image are extracted and particle properties are calculated. Measurement results can be displayed either as trends over time of certain particle groups (e.g. number of particles in a given range of sizes per image), as two- or three-dimensional graphs of certain particle property distributions (e.g. size distribution histogram) or as a combination of both.

The instrument can be operated in two different modes. In online-mode, the instrument is directly connected to the oil circuit of the machine under test. A bypass flow is used to quickly circle oil between the machine and the measurement instrument and to ensure a short reaction time of the measurement. A small branch flow through the flow cell is diverted from the bypass flow by means of a special T-junction, which doesn't segregate oil and contained particles. The stand-alone-mode can be used to evaluate the instrument performance and to generate a knowledge base on possible particles compositions for different wear processes. In this mode, the bypass flow is not used, but an oil sample is directly sucked through the flow cell instead. Measurement results reported in this study were acquired using both modes. Additionally, for some experiments, the system was used in online-mode, but the oil circuit of a running machine was replaced by a beaker with a prepared oil particle mixture.

APPARATUS

Core piece of the measurement instrument is a 1/1.7 inch color CCD sensor array with 14.7 Megapixel resolution and a maximal frame rate of 1 Hz. In combination with the optical system used, it allows to resolve particles down to a size of 1 μm diameter in a field of view of 1.4 mm by 1.0 mm. The white LED flashlight shines through the thin layer of oil in the transparent flow cell, which has a flow channel depth ranging from 100 μm to 500 μm . Flash duration, flow channel depth and flow rate through the flow cell are chosen according to the color of the oil to achieve the required image brightness and to ensure that particles in the image show no motion blurring. For typical fresh engine oil and a flow cell depth of 300 μm , the flash duration would be set to approx. 10 μs and the flow rate through the flow cell would be adjusted to approx. 5 ml/min. When dark oil is analyzed or the oil darkens during the test, either the flash duration is prolonged and the flow rate is reduced at the same time or a flow cell with a thinner flow channel is chosen.

The instrument has two variable speed pumps, which can handle undiluted lubricating oil. They are installed in such a way that inside the instrument the oil to be analyzed is in no contact with any moving parts before the analysis. The smaller pump in the flow cell branch sucks oil through the flow cell, and in online-mode the main pump in the bypass flow achieves a flow rate of up to 2 l/min, depending on oil viscosity. The tubing of the bypass flow has an inner diameter of 4 mm, and typical tubing lengths are 500 mm for

the inlet tube (leading the oil to the instrument) and 1 m for the outlet tube (leading the oil back to the machine). In general tubing lengths should be as short as possible, especially for the inlet tube, and have to be chosen according to how near the instrument can be placed to the sampling point in the oil circuit. The instruments size is 200 mm width, 280 mm depth and 540 mm height and the additional oil volume required when connecting the instrument to an oil circuit is less than 150 ml.

IMAGE ANALYSIS

(See [Fig. 2](#) after last section of paper.)

The analysis of each image comprises basically three steps, preprocessing, particle identification and particle classification. During preprocessing, image background and brightness thresholds are calculated, which makes the analysis mostly insensitive to inhomogeneous or varying image brightness and color. For the identification of particles, each image is converted to a binary image using the background information and thresholds from the previous step, in which each pixel of the image either represents a part of the background or a part of a particle. Each region of connected particle pixels, defined as one particle, is tagged for classification in the next analysis step.

In order to classify particles, the original colored and the binary image are used to calculate more than 30 properties for each particle, which include imaging and geometrical properties. Imaging properties of a particle such as contrast, color or position in the image are used to decide on the sufficiency of the imaging quality of that specific particle. Geometrical properties include among others values for area, equivalent diameter, solidity, and eccentricity, and are used to rate particles either as wear particles, as non-wear particles (e.g. dirt) or as gas bubbles. The feasibility of some geometrical properties depends on the particle size, so that a minimum particle size for each of these properties is defined.

DATA EVALUATION AND INTERPRETATION

At the current stage, instrument control, image analysis and data evaluation are implemented in different software units, because this software structure allows a more flexible way of adapting the method to a new task. Data visualization, evaluation and interpretation very much depend on the task the method is used for. The number of properties calculated for each particle in a series of images allows various data evaluation and two- or three-dimensional visualizations, which all can emphasize different aspects of the particle composition. In combination with set threshold values for growth rate gradients, monitoring growth rates of particle classes (e.g. size or shape classes) over time, allow the prediction of critical situations. It can be very difficult to

define a threshold value for the average amount of particles of a certain class per image, but a sudden and unusual increase of particles of one class is a good indication for a starting or increasing wear. The calculated geometrical particle properties span a multi-dimensional room, in which accumulations of particles in a certain area help to identify the predominant wear process. It was not the aim of this study to develop software, which is able to differentiate various wear processes automatically. But as measurement data shown below suggest, given a substantiated knowledge base this seems to be possible.

Since only a very small portion of the total oil volume is actually analyzed and the generation of wear particles is always a stochastic process, the measurement data always have statistical character. Evaluating trending results, the time resolution of the measurement (i.e. the number of subsequent images averaged values are based upon) and the reliability of data always present a conflict of goals, especially for low particle concentrations in the analyzed oil. The same applies to the feasibility of particle property distributions.

PERFORMANCE OF THE OILPAS METHOD

TEST SET-UP AND PROCEDURE

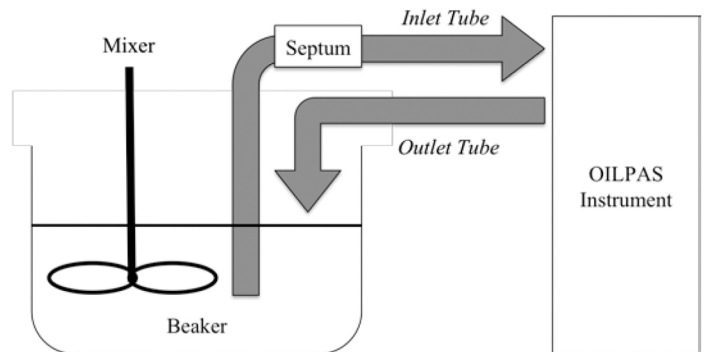


Fig. 3. Schematic representation of the test set-up

[Figure 3](#) depicts the test set-up with the instrument configured in online-mode, which was used to evaluate the imaging properties and the time response of the method. The bypass flow, adjusted to 0.5 l/min flow rate, is circling oil from a beaker with a mixer through the instrument. Fresh SAE 5W-40 semi-synthetic engine oil was used and carbonyl iron powder with an average particle size of 4 μm was used as reference particles, which were either added to the oil in the beaker or injected into the inlet tube through a septum. Adding particles to the beaker is a good possibility to generate a defined particle concentration in the oil volume of the test set-up. The disadvantage is, that although a mixer is used, particles don't dissolve instantly but they tend to float for a little while and stay agglomerated until eventually