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A Video-Based Wear Debris Imaging and Image Processing System for Real Time Wear Debris Monitoring

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Abstract

Wear debris, which is detached from machine components, are valuable information sources to infer the machine operation status. On-line wear debris imaging is a sensing technology that can make use of captured videos of debris in lubrication system to extract debris features for wear analysis purpose. This paper presents a discussion on the challenges arising from on-line wear debris monitoring; including previous approaches, system setup, image processing methods, and recent advancements toward computer vision based debris reconstruction in three-dimension (3-D). Some preliminary results indicate that 3-D wear debris features including volume and thickness can be extracted for machine condition monitoring.

Keywords: on-line wear debris monitoring, video-based imaging, three-dimensional debris reconstruction, ferrography

Introduction

To maintain the long-term reliability of machinery, it is essential to obtain accurate, reliable and timely machine health information so that faults can be detected and pre-emptive maintenances can be economically scheduled. Among available machine condition monitoring techniques, wear debris analysis is commonly used for fault detection and diagnosis [1].

The wear status of mechanical components is highly correlated to the quantity, size, shape and surface characteristics of wear debris [2]. In order to obtain the debris data, ferrography or filtergram based debris analysis have been conducted with high-resolution instruments in laboratory [3, 4]. However, those traditional approaches are being challenged due to the demands of rapid data interpretation in modern condition monitoring. As a result, research focus had been directed towards on-line wear debris analysis [5-7].

In on-line wear debris analysis, approaches such as inductive, capacitance and optical sensing have been developed to capture debris features efficiently [8-10]. These sensing methods were proven to be effective in inferring the wear rate and wear severity of machinery components. However, real time wear debris monitoring still encounters a number of challenges [7]. For instance, although the debris dimension and amount can be explored, debris morphology, which is significant in explaining wear mechanism, is not available by these size- and quantity-based approaches. To address this issue, image-oriented sensing is becoming an attractive alternative due to its ability to provide additional debris information such as shape, surface, thickness and colour.

This paper gives an overview of the image oriented on-line debris sensing. In particular, the application of existing ferrography based approach is introduced, followed by the presentation of challenges in extracting debris morphology for wear mechanism analysis. A 3-D debris imaging and image processing system is described as an improvement of the current 2-D approaches. Finally, a conclusion and an indication of future work are given.

Image Based Wear Debris Examination

To obtain comprehensive debris feature information, image-oriented debris monitoring is preferred [11] and this is normally conducted off-line. To analyse wear debris, oil samples need to be taken from the lubrication system, and wear debris are separated and placed on a glass slide to be imaged by using microscopy, with features such as shape and colour observed [12]. Furthermore, instruments with a high resolution are adopted to extract more detailed debris feature information such as surface texture [13, 14]. Another improvement involves extending debris description into 3-D [15]. It can be seen that these high-resolution imaging approaches enable us to extract more debris information, in particular regarding their shape and surface, so that the debris type can be identified for wear mechanism assessment. To make the debris analysis less time consuming, expert systems were constructed to provide more efficient operations and higher user-friendliness in data interpretation [16]. For example, a fuzzy grey system was reported to automatically classify wear debris into six categories based on individual debris features [17]. However, due to the complex operation and special instruments required, these methods are mostly applied in the laboratory.

Morden condition monitoring demands for real-time data acquisition and interpretation, where debris are often analysed in an on-line process. Attempts were made to develop an on-line method for real-time analysis [18-20], which enable to acquire debris images from an operating machine. A wear debris monitoring system called LaserNet Fines was developed for in-situ wear debris analysis by measuring the size distribution, concentration and shape [18]. To capture small wear debris, an on-line microfluidic chip with dark-field imaging was built to measure debris sizes in a sub-micrometer range [19]. An on-line visual ferrograph was developed to obtain debris colour and concentration [20]. Recently, a 2-D wear debris image separation approach was developed to analyse individual wear debris for estimating debris quantity and equivalent dimension [21]. Compared with traditional on-line debris monitoring approach, image-oriented methods provide more comprehensive debris features.

One limitation of the aforementioned on-line debris monitoring systems is that only 2-D images of wear debris are captured. Wear debris are 3-D objects and may have dissimilar morphologies in different views. For instance, identification of fatigue chunk, laminar and sliding debris often requires their shape, surface and height information [15], of which the height information cannot be provided using the 2-D images. Therefore, an efficient imaging strategy to capture and characterise 3-D debris features is needed to further improve the capability of the existing on-line wear debris monitoring systems. The following sections present the development of a 3-D debris imaging system for on-line condition monitoring.

Video Based On-line Debris Analysis

A video based debris sensing strategy was developed for efficient examination of individual wear debris features in multiple views. A schematic diagram of the 3-D reconstruction system is shown in Fig. 1 [22]. Wear debris in the lubrication oil are collected by pumping the oil from the tank to a fluid channel, where the video of those moving debris is recorded by a digital camera together with a microscope. The dimension of the fluid channel is 6×0.3 mm to ensure that the debris move and rotate in a laminar flow condition. When the wear debris are rotating in the channel, their features in different views are recorded in the video.

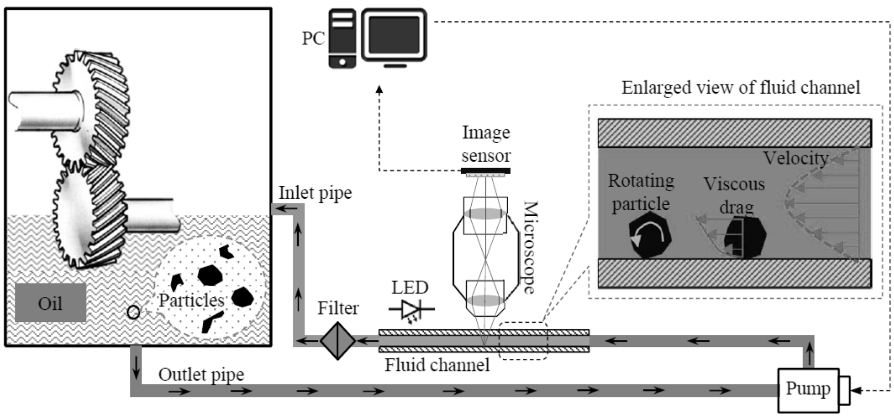

Fig. 1: Wear debris 3-D reconstruction system

One problem arising from the on-line debris video is image blurring caused by the motion of the debris when the video is captured. By using a localised Wiener filter, this type of blur is removed [23]. The improved video is then processed as explained below.

The Frame Work of Individual Debris Processing

To characterise 3-D wear debris features, a framework of video processing is developed, which includes three steps, that is, debris extraction, debris tracking and 3-D debris reconstruction. Fig. 2 illustrates this framework.

Wear Debris Extraction

Due to oil movement, contamination and/or oxidation, the background intensity varies, which makes it difficult to separate wear debris from the background. Hence, an adaptive debris extraction method is required. The Gaussian Mixture Modelling (GMM) [24] is applied to identify the debris in the video. With the pixel intensity modelled by a combination of three Gaussian distributions, the pixels can be divided into two groups: background and debris pixels. In particular, a background Gaussian is firstly estimated according to the severity of intensity variation. Next, pixels matched with the background Gaussian are regarded as background ones, while the rest pixels form the extracted debris. Finally, all the Gaussians are updated for the next video frame. An illustration of the extraction is given in Fig. 2 (a).

Tracking Wear Debris

To construct a 3-D profile of a wear debris in multiple views, the debris has to be tracked in the video using a multi-object-tracking process. To do so, the wear debris is represented as a vector of its centroid and morphology. A Kalman-filter is applied to estimate the debris location in the video frame [25]. Finally, data association is carried out to associate the observation and the prediction of the wear debris to determine its position. The tracking result of a debris video captured from a wear test machine is shown in Fig. 2 (b).

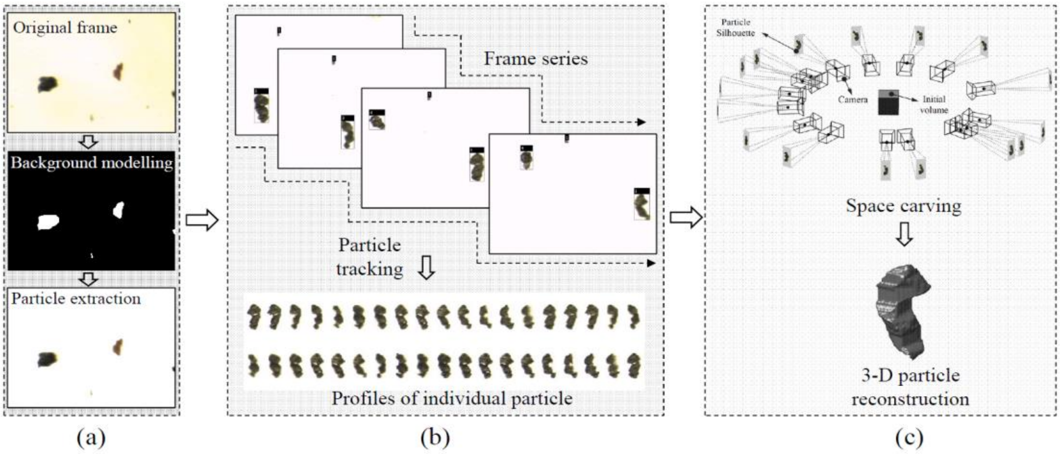

Fig. 2: Framework of the video processing. (a) debris extraction; (b) debris tracking; (c) 3-D debris reconstruction

Debris Reconstruction

The reconstruction of a 3-D debris is casted as a space carving process [26]. The carving operation is conducted with 16 debris profiles and an initial volume, shown in Fig. 2 (c). Each voxel in the initial volume is projected back to a pixel in a profile plane according to the camera geometric parameters. If the projected pixel is outside the profile, the corresponding voxel in the initial volume is discarded. By repeating the projection with the rest of the voxels in the initial volume, the remaining voxels compose the carved result under this profile. After the initial volume is carved by all the 16 debris profiles, the finally remaining voxels form the 3-D approximation of the wear debris, as shown in Fig. 2 (c).

The 3-D wear debris is obtained after the three steps accomplished. Debris features, such as volume, thickness, height aspect ratio, are available. In particular, the volume allows an approximation of the debris mass, which helps to estimate the material loss. Unlike the existing wear debris analysis approaches, debris thickness can be obtained so that this information can be used to differentiate fatigue chunk debris from sliding debris – two debris types have similar boundary features in traditional 2-D image and can be difficult to distinguish. An automatic image characterisation and debris identification process can also be developed for on-line condition monitoring.

Discussion and Future Work

In this paper, a video based debris image acquisition and processing method is presented. This approach is able to provide 3-D debris information for in-depth wear analysis and is a potential for on-line monitoring. Compared with the laboratory based techniques, this method allows efficient data collection with a lower cost in instruments and human operation. Meanwhile, as an on-line method, it can outperform the existing systems by providing more debris features such as volume and thickness, which enable to classify debris with similar shape features in their 2-D images. This function will significantly advance the capability of the existing on-line wear debris analysis methods as debris type is essential for wear mechanism assessment. The method is still in its development phase. A number of issues need be addressed to make it practical. For instance, the video quality is usually limited due to the commonly occurred lubrication contamination. Meanwhile, due to debris motion and the limited depth of field, the debris images are often blurred, making the feature extraction difficult. Currently, research is being conducted to improve the image quality so that accurate and reliable debris features can be obtained for debris classification and wear analysis.

Conclusion

To meet the demand for real-time wear debris analysis for condition monitoring, a prototype video based system was recently developed to capture debris images in multiple views. Further image processing work is conducted to separate 2-D debris from their background, track them in different frames and reconstruct 3-D debris. This method improves current on-line wear debris monitoring by offering more comprehensive wear debris information. Compared with other debris imaging approaches, it provides the thickness as well as volume information which can be used to estimate material loss and to assess wear mechanisms. Once the system has been developed, the entire process, including video recording, debris extraction, tracking and reconstruction, and debris feature characterisation, will be automated, making it a feasible option for on-line wear debris monitoring.

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