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Prediction on wear of a spur gearbox by on-line wear debris concentration monitoring

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ABSTRACT

The aim of this work is to develop a method for quantifying and predicting gear wear based on on-line wear monitoring. A model of wear debris concentration has been built based on Kragelsky's method with different wear coefficients in corresponding wear stages. A gear test rig with oil-bath lubrication for accelerated wear test was built, and a full-life wear monitoring test was performed by employing an on-line visual ferrograph (OLVF). An index of particle coverage area (IPCA) characterizing wear debris concentration and an OLVF ferrogram were obtained by sampling in-use oil every 2 min. The experiment results indicate that the IPCA curve is consistent with the proposed model, and the early-warning signs of abnormalities can also be observed. Additionally, depositing experiments show that appropriate depositing time (usually not less than 30 s) is crucial for a valid OLVF sampling. Therefore, it is feasible to predict gear wear by on-line wear debris concentration monitoring.

1. Introduction

Gear wear is one of the most common causes resulting in failures in power transmission systems [1–3]. There are mainly three different wear mechanisms: adhesive wear, abrasive wear and fatigue wear. And a mixed form of the above three wears may occur in the service of a gearbox due to complex and ever-changing lubricating states [4]. Although wear mechanisms have been comprehensively studied [5,6], gear wear has not been well understood due to its complex characteristics, such as the system-dependent, time-dependent and physical coupling [7].

Wear occurs in tiny gaps between contact surfaces, it is difficult to measure wear without changing contact states of tribo-pairs in real time. Indirect approaches, such as acoustic, temperature and vibration, have been used to detect indirect physical changes caused by wear to deduce wear state of tribo-pairs [8–10]. Terminal wear failures have been successfully identified by these methods already, but there are still some barriers for abnormal wear initiation and progression [11]. Comparatively, wear debris carries direct information about wear degree and mode, and thus a wear process can be depicted by extracting the concentration, size and morphology of wear debris [12,13]. In addition, wear debris monitoring can detect gear surface pitting much earlier than vibration analysis [14]. Thus, on-line wear monitoring based on wear debris analysis is useful for gear wear prediction and maintenance scheduling to avoid functional failures.

Different techniques of wear debris analysis have been proposed [15,16]. Spectrographic oil analysis (SOA) is effective for elemental precise analysis of wear debris with the size under 10 μm [17]. Off-line ferrography, almost covering the size range of wear debris from a few microns to hundreds microns, has been proved to be useful for identifying wear degree and mode [18]. However, both methods are of low automation degree and need auxiliary instruments or chemical agents. Additionally, off-line sampling is even a tough task for some equipments, such as a wind turbine gearbox high above the ground, which leads to the time-dependent wear process not to be correctly characterized due to a long sampling interval. Although sampling interval can be theoretically reduced to meet the requirements of on-line wear monitoring, information lagging is inevitable due to tedious pre-processing of oil samples. Furthermore, oil depletion caused by frequent off-line sampling cannot be ignored.

However, for real-time wear monitoring, on-line visual ferrograph (OLVF) was developed based on magnetic deposition and image analysis [19–21]. OLVF allows high-frequent sampling from a fixed position without oil sample pre-processing and extra oil loss, and expresses obvious advantages in tracking a fast-changing wear process. Since OLVF ferrograms have low resolution and many interferences, such as bubbles, extracting visual features is

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Nomenclature

h_i	wear depth of gear tooth flanks at a point i (mm)
a_i	half Hertzian contact width at a point i (mm)
c, b	coefficients (s^{-1})
n	rotational speed (rpm)
n_1,n_2	rotational speeds of pinion and wheel (rpm)
t	time (s)
Z_s	number of engagement pairs
Z_{1s},Z_{2s}	numbers of engagement pairs of pinion and wheel
A	$A = 2\rho B(n_1 z_1 Z_{1s} \int a_i \eta_i \, dl_1 + n_2 z_2 Z_{2s} \int a_i \eta_i \, dl_2)$
I_h	wear coefficient
I_{h0},I_{hs}	wear coefficients at the initial moment and steady-state stage, respectively
S	wear debris concentration (ppm)
S_0, S_{eq}	wear debris concentrations at the initial moment and steady-state stage, respectively (ppm)
V	volume of lube oil (L)
B	face width (mm)
l_1, l_2	meshing profile curves of pinion and wheel
z_1, z_2	numbers of teeth of pinion and wheel
m	wear debris generation rate (mg s^{-1})
m_0,m_s	wear debris generation rates at the initial moment and steady-state stage, respectively (mg s^{-1})
f	sedimentation coefficient of debris (s^{-1})

Greek letters

ρ	density of pinion and wheel (mg mm^{-3})
η_i	sliding coefficient at a point i

more challenging than using off-line ferrograph. Image projection transformation and full binary tree based image division have been utilized for extracting macro and statistical features of wear debris chains including thinning ratio, chain length and chain width [22]. Wear debris separation using gray level and integrated morphological features has been realized to extract more features of wear debris [23]. Different wear processes can be distinguished reliably by OLVF, and then a new experimental method for assessing anti-wear properties of lube oil in different wear stages has been developed [24]. OLVF has also been applied in engine bench tests to capture abnormal wear [25,26].

Above research works put aside system-dependent tribological behaviors and were limited to capture abnormal signals from monitoring results or focused on a single OLVF ferrogram. It remains difficult to explain the time-series data from OLVF for quantifying and predicting gear wear. In this work, wear debris concentration in different wear stages is modeled to reveal the relationship between wear debris concentration and gear wear rate in service. The results indicate that full-life monitoring results of a gearbox by OLVF are consistent with the proposed model. Therefore, it is feasible to predict gear wear by on-line wear debris concentration monitoring.

2. Modeling wear debris concentration of a spur gear box

2.1. Gear tooth wear in Kragelsky's model

Kragelsky proposed a model to calculate the wear depth h_i of a gear tooth at a point i as follows [27]:

$$h_i = 2a_i \eta_i n t Z_s I_h \quad (1)$$

where a_i is the half Hertzian contact width (mm), η_i is sliding coefficient, n is rotational speed (rpm), t is running time (s), Z_s is the number of engagement pairs and I_h is wear coefficient. The wear of a spur gear pair with different pinion cycles can be calculated as shown in Fig. 1. Assuming that the wear debris generation rate is equal to wear rate, wear debris concentration S can be obtained from

$$S = \frac{A I_h}{V} \cdot t \quad (2)$$

where $A = 2\rho B(n_1 z_1 Z_{1s} \int a_i \eta_i \, dl_1 + n_2 z_2 Z_{2s} \int a_i \eta_i \, dl_2)$, the parameters are described in the nomenclature. Fig. 2 indicates that a considerable change, which increases linearly with the running revolution by ignoring the removal of wear debris, occurs in wear debris concentration. But the variation of mesh stiffness is

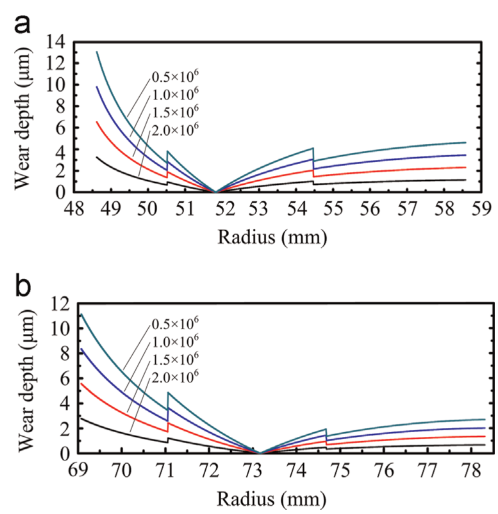

Fig. 1. Theoretical wear development of (a) pinion (b) wheel. Gear data, see Table 1, $n = 1450$ rpm, pinion cycles 0.5×10^6 to 2.0×10^6, $I_h = 1.1 \times 10^{-8}$, applied load 200 N m on the pinion. Pitch radii are 51.8 mm and 73.2 mm respectively.

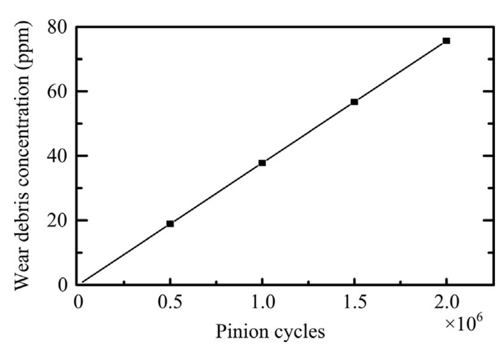

Fig. 2. Wear debris concentration with different pinion cycles. Calculation parameters, see Fig. 1.

insensitive to gear wear as shown in Fig. 3, which directly leads to a weak vibration excitation.

In a gearbox with oil-bath lubrication, the lube oil is continuously stirred so that the wear debris can be assumed to be evenly distributed in the lube oil. Considering the sedimentation of wear debris, the relationship between wear debris concentration S (ppm) and wear debris generation rate m which is defined as the incremental debris mass in lube oil caused by gear wear in unit time (mg s^{-1}) can be built as [28].