Review on online inductive wear debris monitoring technology

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Abstract: Online oil monitoring technique is now an important development means to monitor wear condition and diagnose wear fault real time. Inductive wear debris monitoring is the research hotspot in the current online oil monitoring for its unique characteristics. Based on the current domestic and international online inductive wear debris monitoring, the development trend to the online inductive wear debris monitoring technology were given. Then, the positive and inverse problems of numerical analysis of inductive wear debris monitoring are analysed. Based on the above, the difficulties and shortages of online inductive wear debris monitoring are studied and the development trend and research focus of online inductive wear debris monitoring are discussion to provide for the oil online technology research.

1 Introduction

Online oil monitoring technique is now an important development means to monitor wear condition and diagnose wear fault real time, it can judge the operation status of the equipment by monitoring the lubricating oil in real time. The advantages of online oil monitoring mainly include the continuity of monitoring process, real-time performance, synchronisation of monitoring equipment, and the running state of monitored objects, compared with offline monitoring and portable monitoring. The online oil monitoring is more sensitive with higher accuracy and reliability compared with vibration and functional parameters monitoring [1–4]. So online oil monitoring is suitable for equipment in large noise, multi vibration sources, and obvious external interference.

The development of oil analysis technology is mainly reflected in the technical level of the oil monitoring system, analysis of abrasive particle, lubricant state monitoring, and the functions of the oil analysis and monitoring instrument. The traditional oil monitoring technology mainly adopts the offline method, such as particle counting method and spectral method, which can realise the offline impurities monitoring of oil. However, the offline mode is not only time-consuming, but also costly, due to the need of sampling and reanalysis, and the lagging of measurement return results. So the offline monitoring mode has been gradually replaced by online monitoring technology in many application fields.

The wear debris monitored in the lubricating oil are produced by the wear of the friction pair of the equipment, and the characteristics of the debris can represent the most important information of the wear process. In the wear failure of mechanical equipment, the wear faults induced by debris accounted for 82% of the total wear faults, while non-debris induced wear faults only accounted for 18% as shown in Fig. 1. The debris-induced fault mainly contains corrosive wear and abrasive wear and fatigue wear while abrasive wear accounted for 66% in the whole wear types. By accurately detecting the wear debris in the oil fluid, it can predict the wear failure effectively and avoid the loss caused by equipment wear.

In the initial stage of mechanical abnormal wear, the size of wear debris is tiny, usually starting from 10 μm, and the relationship between wear form and wear debris size is shown in Table 1. In the three stages of accelerated wear, normal wear, and severe wear, the tiny wear debris in the oil have the development trend characteristics of time, and the larger the debris size, the more serious the wear. At present limited by the online detection and detection method of wear debris, it cannot be effectively identified especially for the tiny ferromagnetic debris (50 μm −100 μm) in the initial stage of wear failure [5, 6]. Professor E. c. Fitch with the help of BHRA (British Hydromechanics Research Association) carried out a 3-year investigation into hydraulic machinery and found that the size of metal wear debris decreasing five times in lubricating oil, possibility to wear failure reducing 50 times. Therefore, it is more important to monitor and identify wear debris online to reduce the wear failure of mechanical equipment.

2 Research of online inductive wear debris monitoring

2.1 Theory of inductive wear debris monitoring

Biot-Savart's law shown in (1) is the fundamental law of electromagnetic field. In principle, the law can be used to calculate

\begin{equation}
\text{Biot-Savart's law}
\end{equation}
the magnetic field generated by the stable current of any distribution, and the source of other indirect calculations is still Biot-Savart's law.

\[
dB = \frac{\mu_0}{4\pi} \frac{dl \times r}{r^2}
\]

Maxwell's equations are the important equations in inductive wear debris monitoring shown in (2) and (3). In the equation, the electric field generated by the change of magnetic field is considered, regardless of the magnetic field generated by the change of the electric field.

\[
\nabla \times H = J
\]

(2)

\[
\nabla \times B = 0
\]

(3)

\(H\) represents magnetic field intensity and \(B\) represents magnetic induction intensity. The relationship of \(H\) and \(B\) is shown below.

\[
B = \mu_0 H
\]

(4)

In solving practical wear debris monitoring, as direct solving Maxwell's equations are often not convenient, it is needed to introduce different electromagnetic parameter to establish a partial differential equation. Vector magnetic potential of \(A\) and scalar magnetic potential of \(\phi_m\) are two parameters introduced according to the divergence and curl of the magnetic field, and they satisfy equation below

\[
\nabla^2 A = -\mu J
\]

(5)

\[
\nabla^2 \phi_m = 0
\]

(6)

Hypothesis of inductive wear debris analysis mainly includes the alternating magnetic field in the monitoring sensor coil satisfies the condition of the quasi-static field and the magnetic pressure has linear permeability. The assumption of inductive wear debris analysis is shown below.

(i) The loop of the coil is the coaxial loop.

(ii) There is an infinitely thin insulation between the turns of the line, and all the loops are tightly packed with all the space occupied by the coil.

(iii) The coil wire in the radial direction and the axial direction is uniformly twined, the current is equally distributed along the section, and the direction of current density and the positive form of the symmetrical axis has the right-hand spiral relationship.

(iv) The axisymmetric coil is in an infinite vacuum.

(v) When the ferromagnetic debris appear in the axisymmetric structure, its symmetry axis and coil coaxial are all in the infinite vacuum.

The analytical solution of inductive wear debris monitoring consists of establishing and solving partial differential equation or integral equation, and the method of strict solving partial differential equation is the variable separation method. The main method to solve the integral equation strictly is the mathematical transform method. The analytical solution can be expressed as the explicit expression of the known function, so as to calculate the exact numerical result. It can also be used as the test standard for approximate solutions and numerical solutions. The analytic solution can observe the internal relation of the problem and the function of each parameter to the numerical method.

### 2.2 Development of inductive sensors

The composition of wear debris is the same as that of friction pairs, as the debris produced by mechanical wear are formed by the falling of surface of the friction pair. There are many kinds of friction pairs in the equipment, and there are different elements in parts prone to wear. For example, the representative elements of the main friction pairs in the transmission system are Iron (Fe for short) and Chromium (Cr for short) and Nickel (Ni for short) in transmission gear, Iron and Silicon (Si) in seal components, Iron and Chromium in gear bearing. It is observed that almost all the friction pairs contain Fe, and different friction pair has different contents of iron element. So the concentration change of the ferromagnetic wear debris in lubricating oil can reflect the wear condition of most friction pair. The change of size and concentration can be taken as the theoretical basis for judging the degree of friction wear and it is more meaningful to identify the micro ferromagnetic particles in the early stage of equipment wear.

In the online monitoring of wear debris, the most research and application are the inductive measurement method. The inductive monitoring is the research hotspot in the field of the current online monitoring for its unique characteristics. First, the inductive monitoring can count debris amount and distinguish debris material. Second, the inductive monitoring sensors are easy to fabricate and not easy to suffer the interference outside temperature and vibration. Third, it is not easily affected by the oil bubble and the interference of impurity with high accuracy [7, 8].

In inductive wear debris monitoring, the sensor plays an important role as the key component. Many online inductive wear debris monitoring sensors have been manufactured in Canada, Britain, Japan, the USA, and Germany company and Table 2 shows the performances of the main online inductive sensor abroad.

Compared with the developed countries in the world, the oil monitoring research in China started later. In 1987, the first online iron spectrometer was developed by xi ‘an Jiaotong university's lubrication theory and bearing research institute in China. Much thorough research has been carried on in Wuhan University of Technology, Ordnance Engineering College, university of electronic science and technology, Beijing Institute of Technology. The wear debris monitoring sensor has gone through the development of a single coil inductance measuring coil, double coil, to differential three coil shown in Fig. 2. In the first stage, only one coil is used to achieve exciting and induction, in the second stage two coils are used to achieve exciting and induction and in the third stage differential two differential coils are used to achieve exciting and one coil is used to achieve induction in inductive wear debris monitoring. In terms of actual online inductive wear debris monitoring, accuracy of the measured results usually depends on several measurement conditions, such as applied voltage, signal frequency, internal impedance of devices under tests, and so on. For example, inductance value is strongly affected by parasitic impedance (such as stray capacitance) especially in the high-frequency range (in general, more than kHz range).

So far, various research has been carried out on inductive wear debris monitoring at home and abroad, and the related research achievements are mostly concentrated in the sensor and its improvement, but the accuracy of most online inductive wear debris monitoring is in the 100 μm and it is unable to effectively identify wear debris in <100 microns at the early wear of mechanical equipment.

### Table 2 Inductive sensor performance

| Manufacturer | Sensor     | Nominal bore | Detection limit (μm) |
|--------------|------------|--------------|----------------------|
| gasTOPS      | Metalscan  | 9.5 mm       | 100 μm               |
| gasTOPS      | Metalscan  | 19 mm        | 200 μm               |
| gasTOPS      | Metalscan  | 31.8 mm      | 290 μm               |
| kittkawe     | FG         | 10 mm        | 40 μm                |
| takuso Sato & M· | TechAlert10 | Not stated | 50 μm                |
| Linzer       |            | 6.3 mm       | 70 μm                |
| hydac        | MCS13      |              |                      |

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3 Positive and inverse problems of numerical analysis in online inductive wear debris monitoring

3.1 Positive problem

The positive problem of numerical analysis in online inductive wear debris monitoring is to find out the law of field quantity over time and space distribution in electromagnetic fields. The whole numerical analysis process of the positive problem is shown in Fig. 3. From Fig. 2, it can be seen that a variety of numerical calculation method is the core which can transform the continuous mathematical model into equivalent discrete mathematical model to get the electromagnetic characteristics by adopting appropriate idealised assumptions and accurate definition of wear debris monitoring condition (mainly including initial conditions and boundary conditions). The common basic point of numerical analysis positive and inverse problems of online inductive wear debris monitoring lies in the calculation area of a given field, the composition and characteristics of various regional materials (media), and the characteristics of the excitation source [9, 10].

The numerical method can be used to describe the electromagnetic field problem directly in the form of numerical and program. In the numerical method, the difference is usually replaced by differential, and the integral is replaced by finite sum, and the problem is solved by solving the difference equation or algebraic equation. Compared with analytical method, numerical method has advantages in many aspects. Users can solve practical wear debris monitoring analysis without a highly specialised knowledge of electromagnetic field theory, mathematics, and numerical techniques.

3.2 Inverse problem

The inverse problem of online inductive wear debris monitoring and analysis is to optimise the online inductive wear debris monitoring sensor according to the ideal performance index or parameter of the sensor. At present, the solution to the inverse problem of online inductive wear debris monitoring and analysis is to decompose it into a series of positive problems, and then adopt a certain optimisation method to achieve the end optimisation design by iterative solution as shown in Fig. 4. In the inverse problem, numerical method makes the analysis of the electromagnetic field problems from the classic analytical method into the numerical analysis method of discrete system, which makes many difficult complex analytic problems of electromagnetic field are likely to get the high accuracy through the electromagnetic field of computer aided analysis of discrete numerical method. Compared with relative positive problem, the inverse problem is solved with large computation and occupies more computer memory and CPU time.

4 Difficulties and shortage of online inductive wear debris monitoring

In actual online inductive wear debris monitoring, the problems faced mainly include: interference (mainly including electromagnetic interference, vibration and temperature), wear debris depositing, and impurities [11–14].

The specific existing shortage in the online inductive wear debris are shown as follows.

(i) At present, the research on online inductive monitoring technology mainly focus on the hardware, the data analysis system is insufficient, and the multi-level fusion diagnosis is lacking.

(ii) The accuracy of online inductive monitoring sensor is not high, and the reliability remains to be verified. Most of sensors are still in the experimental stage, and the products that are actually used in engineering practice are rare.

(iii) Now the related standard of inductive wear debris monitoring is lack, and the online monitoring theory are mainly based on the sphere wear debris rarely considering the different wear debris shape of various wear fault.

Fig. 2 Development of wear debris sensor

Fig. 3 Positive problem solution process

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The research hot spots of inductive online wear debris monitoring are embodied in two aspects of basic research and application research. Basic research work mainly focuses on the accuracy, technology integration, and exploration of the inherent law and so on. Application research mainly includes various information processing strategies, and development of a comprehensive management decision system. The specific research hot spots are discussed to provide for the oil online technology research as follows:

(i) One hot spot is the theoretical research of inductive oil monitoring, real-time status discrimination, and integration.
(ii) Another is the development of online inductive wear debris monitoring sensor to improve the practical application of sensor reliability level. The development of integrated online oil sensor enables the sensor to be capable of signal processing, data fusion, self-calibration, self-diagnosis, and potential automatic reasoning ability.

(iii) The third is the fusion prediction and diagnosis of online oil monitoring technology based on multi-methods: combination of multiple online monitoring methods like oil, vibration, and performance parameter monitoring methods.

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Fig. 4 Inverse problem solution process

5 Development trend and research focus of online inductive wear debris monitoring

The integration of online inductive wear debris monitoring technology and the current rapid development of high and new technology is the motive force of inductive wear debris monitoring development. Along with the development of computer technology, network communication technology, and the data fusion technology, the online inductive wear debris monitoring is developed to the integration, intelligence, network direction development.

Under current technical and economic conditions, the online inductive wear particle detection cannot completely replace the offline detection. In the future, online oil monitoring, offline oil monitoring, portable oil monitoring will exist at the same time with mutual penetration. In some specific industries, online oil monitoring will be the main means, and it will be the main direction of detection and diagnosis technology research for a long period in the future. The online oil monitoring represents the forefront of equipment lubrication and wear fault diagnosis technology. The inductive monitoring mode gets wide attention in the field of oil monitoring technology for its significant advantages.

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