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Research Article

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Research on the detection of metal debris with micro inductive sensor embedded in lubricant

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ABSTRACT

The detection of metal debris in oil is very important for monitoring the machinery. Based on the electromagnetic induction principle, a micro inductive sensor is designed and fabricated. This sensor is embedded in oil pipe as the oil circulates in the oil system. The micro-sensor can test more oil sample than other micro inductive sensor with micro pipe. An analog on-line detection system is built and the detection experiments are carried out in this paper. The oil samples with copper debris and iron debris are detected separately. The size of debris is between 88μm and 100μm. A simulation is carried out to analyze the trace of debris in oil with the software of Comsol. The accurate position of debris in oil pipe can be obtained according to the simulation result. The position and the size of debris relate to the inductance signal. With the accurate position of debris, the size of debris can be obtained according to the value of the inductance signal. The study designs an inductive sensor, and it can do high-through sample detection. The simulation gives a model to analyze the trace of metal debris in oil. The method has reference value for forecasting mechanical failure and monitoring the machinery. The simulation lays the foundation to study the distribution of metal debris. It is useful to study the relation between the size of debris and the inductance signal.

Key words: Metal debris detection, Micro sensor, Inductive sensor, On-line detection

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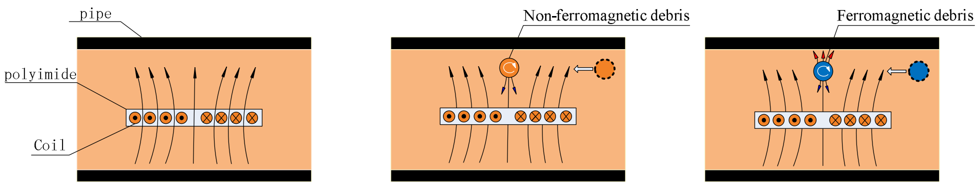
INTRODUCTION

The mechanical device produces metal debris in working. The metal debris always suspends in oil system and damages the mechanical device. Research shows that about 80 percent of mechanical faults are caused by abrasion failure and lubrication failure. About 82 percent of these failures are caused by debris [1]. The research reports of Shell Company indicate that about 60 percent of mechanical faults and 38.5 percent of gear faults are caused by abrasion [2], and the wear fault caused by particles takes 82 percent of abrasion [3]. So the research of detecting metal debris in oil is important for monitoring the working condition of machinery. It is also useful to decreas the serious accident and economic loss [4].

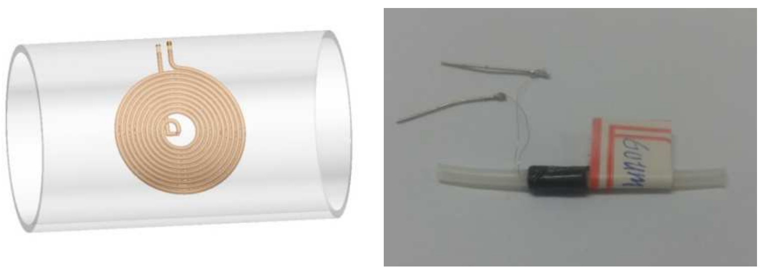
The debris detection can be classified into offline detection and online detection. The offline detection methods have some shortcomings such as long test cycle and high cost. As a result, researches turn to focus on online debris detection recently [5, 6]. The online debris detection includes the methods such as the online ferrography analysis, the ultrasonic testing, the capacitance detection and the inductance test. The online ferrography analysis evolves from the traditional ferrography analysis. One online ferrography analysis method was designed by Hongfu Zuo [7]. In the method, the ferromagnetic debris in oil was absorbed to the observation wall by electromagnet force. Then the debris was observed and analyzed in real time by utilizing microscope. However, this method is powerless in detecting non-ferromagnetic debris [8].The high frequency ultrasonic energy is introduced in the ultrasonic testing. The ultrasonic energy propagates through the lubricant oil in the form of waves. When there is debris in the wave path, part of the energy will be reflected. So, the size and the position of debris can be detected with the ultrasonic testing. However, the composition of the debris cannot be obtained by ultrasonic testing. In addition, the sensitivity of ultrasonic sensor is easily interfered by the temperature of the lubricant [9].The capacitance debris detection can get the size information of debris through the capacitance changes. It has advantages such as simple structure and high resolution. However, it is also unable to distinguish between ferromagnetic debris and non-ferromagnetic debris [10]. Recently, the inductive sensor was used to detect the metal debris in lubricant. The principle is that the non-ferromagnetic metal debris decreases the sensor inductance. On the contrary, the ferromagnetic metal debris increases the sensor inductance. Therefore, the ferromagnetic debris and non-ferromagnetic debris can be distinguished according to the rise or the decline of the sensor inductance, and the size of debris can be discriminated in light of the change of inductance. A micro inductive sensor was designed based on the Coulter Counter by Li D [11, 12]. In the experiment, iron debris with the size between 75μm and 105μm is detected, and the changing rate of the sensor inductance is between 0.091% and 0.167%. The experimental results indicate that the inductive sensor has the ability to detect tiny metal debris. However, the micro coil is twined in the oil pipe, so the oil pipe should be thin. Therefore, the oil that the inductive sensor can detect is too little to include the wear information of machinery. In former work, the size of micro inductive sensor is optimized [13, 14] in order to make it a good sensitivity. In this paper, an optimized sensor is embedded into the lubricant pipe to detect metal debris in flowing oil. With this method, a great deal of lubrication oil can be detected because the size of oil pipe is larger than other inductive methods with micro pipe. The flowing copper debris and iron debris with the range between 88um and 100um are detected in the experiments. The flow trace simulation of metal debris in oil pipe is built by using the software of Comsol. In this simulation, the flowing trace of debris is analyzed.

The test principle of inductive sensor

The principle of detecting metal debris with micro inductive sensor is shown in figure 1. The micro coil surrounded by protective film is deposited into the oil pipe. There will be an alternating magnetic field around the micro coil while the alternating current flow the coil. The relation between current and the magnetic field is shown in figure 1(a). The magnetic field will be affected while non-ferromagnetic metal debris passes through the micro coil [15], which is shown in figure 1(b). Then eddy current is generated in the metal debris because of the alternating magnetic field. The direction of the magnetic field generated by eddy current is opposite to the magnetic field generated by the micro coil. Therefore, it makes the magnetic field of the micro coil decrease. The decrease of the magnetic field causes the reduction of the sensor inductance. So, the equivalent inductance of the coil decreases while the non-ferromagnetic metal debris passes through it. The magnetic field of the micro coil with ferromagnetic metal debris is described in Figure 1(c). The ferromagnetic debris also causes the eddy current effect, which decreases the coil inductance. But the ferromagnetic metal has large permeability, and the magnetic induction will increase due to the magnetization effect. The magnetization effect is greater than eddy current effect, so the inductance of micro coil will increase because of the large permeability of debris [16]. Therefore, the material of the metal debris can be recognized according to the increase or the decrease of the inductance. The debris's size can be identified by the quantity of inductance's change.



(a) The coil with no debris (b) The test of non-ferromagnetic debris (c) The test of ferromagnetic debris
Fig. 1: The test principle of the inductive sensor



(a) The model of micro coil in pipe (b) The entity of coil and pipe
Fig. 2: The micro coil and the pipe

The on-line detection of metal debris

The micro coil and the oil pipe are shown in figure 2. There are 10 circles and 1 layer of the micro coil. The inner diameter of the micro coil is 400μm and the outer diameter is 1600μm. The coil is made of copper line, whose diameter is 60μm. The coil is covered with polyimide which is used to protect it from being damaged from oil and particles. The size of copper debris and iron debris are selected between 88μm and 100μm because the metal debris below 100μm is meaningful in reflecting the wear condition of machine [17]. The copper debris comes from particles of pure copper block and the iron debris is from the particles of DT4C. In the experiment, the two kinds of metal debris are mixed into one kind of NO.1 vacuum pump oil separately, and 1mg metal particles mix with 10 ml lubrication oil.

The principle of the on-line experiment is shown in figure 3. The micro coil is connected to the Agilent E4980 LCR testing instrument. The inductance signal of micro coil can be detected by the testing instrument, and the signal is stored in the memorizer. One side of the pipe connects to the injector and the other side is put into the oil pool. The injector is fixed on the heel block, and the back plate is fixed at the slide block. The motor rotates and makes the back plate move along the sliding rail. The moving back plate pushes the injector, so the oil in the injector can be pressed into the pipe finally. The driver, the power and the controller connect with each other, they form the control unit. With the help of control unit, the velocity of the oil can be regulated by adjusting the frequency of the controller.

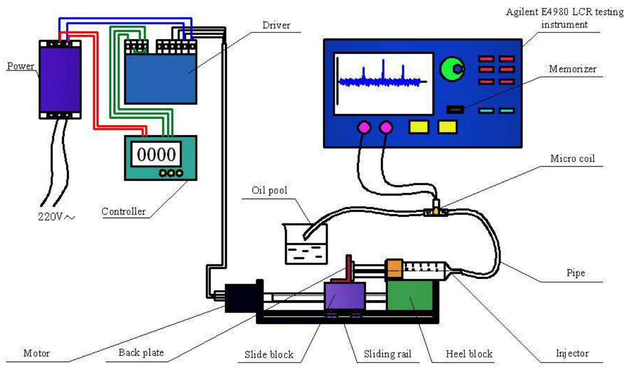


Fig. 3：The draft of the on-line experiment system

The photograph of on-line experiment system is shown in figure 4. The Agilent E4980 is set to the model 'Ls-Rs'. The test frequency is set as 2MHz and the voltage loaded to the coil is set as 1V. For this setup, the response time of the inductance measurement is about 6ms. In order to make the oil flow smoothly, the frequency of the controller is set as 500Hz when the power of the motor is considered. For this setup, the flow rate of oil is 6.8ml/min. The velocity of the oil can be obtained with formula 1.

$Q = \pi R^2 \cdot v$ (1)

Here, Q is the flow rate, R is the inner radius of the pipe and v is the velocity of oil. In the experiment, the value of R is 1mm, and the value of Q is 6.8ml/min. So the velocity of the oil can be calculated. Its value is 0.06m/s.

Fig. 4: The photograph of on-line experiment system

The experimental result of detecting iron debris is shown in figure 5. The positive impulses indicate that the equivalent inductance of the micro coil increases when the iron debris flows through it. The changing rate of the inductance is about 0.025%. The on-line detection of copper debris is shown in figure 6. The negative impulses indicate that the equivalent inductance of the micro coil decreases when the copper debris flows through it, and the changing rate of the inductance is between -0.013% and -0.017%. Therefore, the ferromagnetic debris and the non-ferromagnetic can be distinguished through the positive impulse and the negative impulse. The heights of the impulses in figure 6 and figure

7 are different. This is because the size of metal debris and the distance between debris and the micro coil are different. The size of debris and the distance between micro coil and the debris relate to the inductance signal. When the distance between micro coil and the debris is accurate, the size of debris can be obtained according to the inductance signal. The distribution of metal debris is studied in simulation work preliminarily. The relationship between the size of debris and the signal will be researched in future work.

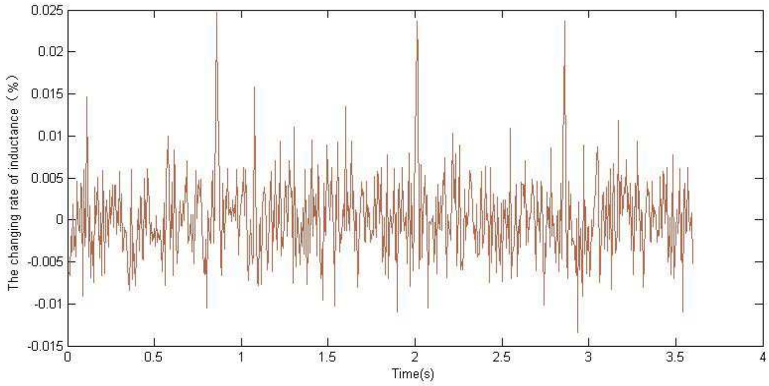


Fig. 5: The on-line test of iron debris

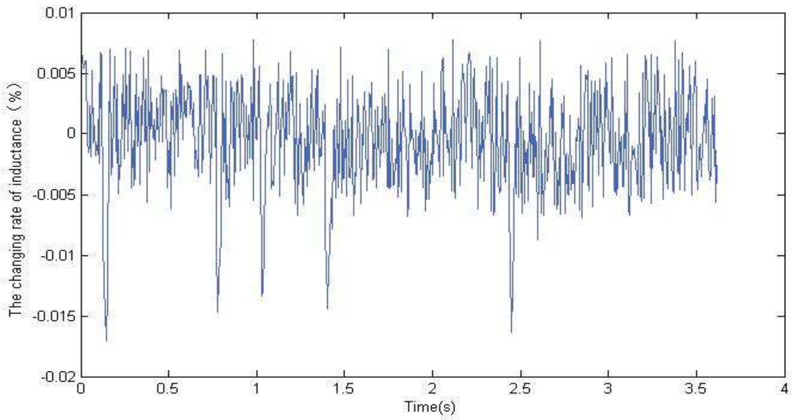


Fig. 6: The on-line test of copper debris

The flow field simulation of experimental system

The flow field simulation model of experimental system is built with the software of Comsol. The flow state of oil relates to Reynolds number. The calculation equation of Reynolds number is shown in formula 2. In the experiment, the kinematic viscosity of oil is about 90cst, the velocity of oil is set as 0.06m/s and the diameter of pipe is set as 2mm. So the value of Reynolds number can be obtained with formula 2. Then the flow state of oil can be confirmed as laminar flow. The particle tracing module is added into the simulation. For this setup, the trace of metal debris can be studied.

$$\mathrm{Re} = vd \,/\, \gamma \quad (2)$$

Here, *Re* is Reynolds number, *v* is the velocity of oil, *d* is the diameter of pipe, and γ is the kinematic viscosity of oil.

The flow trace of iron debris is simulated with 2D model. The intersecting surface of the micro coil sensor is selected as the model plane. As shown in figure 7, the white rectangle indicates the wall of pipe, the yellow rectangle indicates the intersecting surface of the micro coil, and the circle particles indicate metal debris. In the simulation, the length and the width of pipe are set as 10mm and 2mm separately. The model of micro coil is deposited at the center of the pipe. For the model of micro coil and the protective layer, the length of its intersecting surface is set as 1.6mm and the width is set as 120μm.

The materials of models are shown in table 1. They are confirmed according to the real experiment in order to make the simulation accuracy. The mesh generation of the model is set as the fine scale. The right side line of pipe is set as the entrance of oil and debris, the left side line of the pipe is set as the exit, and the other lines are set as a boundary condition of bound-back. The velocity of oil is set as 0.06m/s. The density of the iron debris is set as 7800kg/m^3 and the diameter is set as 100μm. Eight particles are set to enter the entrance of the pipe every 0.005s and these particles are set as uniform distribution to the entrance. The design of the solver is revised in order to match the laminar flow field with the particle tracing module.

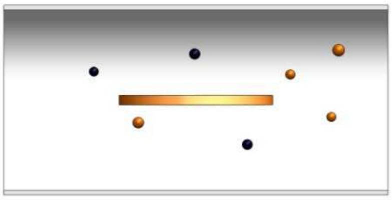


Fig. 7: The diagrammatic sketch of simulation model

TABLE 1：Materials of simulation models

Name	Materials
Micro coil	Copper
Pipe	Teflon
Iron debris	DT4C
Oil	NO.1vacuum pump oil

The distribution of oil velocity is shown in figure 8. As a well know conclusion, the oil at the center of the pipe has a faster velocity than the oil at the both side because of the friction and the adhesion between the pipe wall and flow oil. When the oil passes through the coil, its velocity will be changed. The micro makes the velocity of oil close to the coil decrease. On the contrary, the velocity of oil in some positions is increase. The highest change of oil velocity is from about 0.07 m/s to more than 0.09m/s. Since debris suspends in the oil, knowing the velocity distribution of oil is helpful for analyzing the trace of debris.

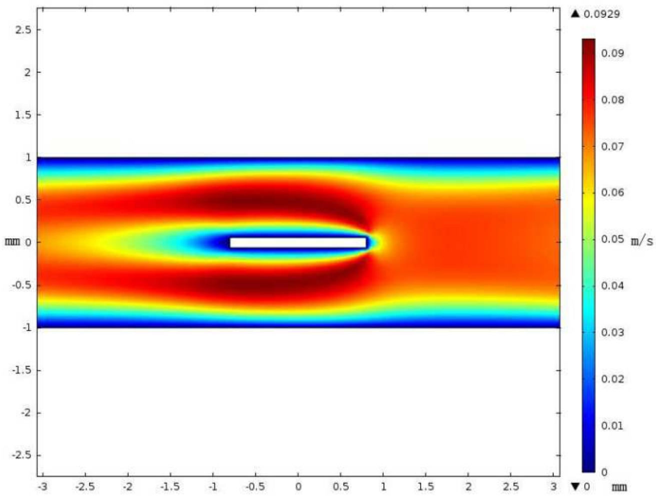


Fig. 8: The velocity distribution of the oil

The traces of particles are shown in figure 9. The center of the entrance line is set as the origin of coordinates. The direction that the debris flows is set as X axis and the upward direction of the pipe in figure 8 is set as Y axis. The unit is set as millimeter and the center of the micro coil is at the coordinate of (5, 0). Then 4 traces of iron debris are given out as an analysis. These particles are released at the same time and they are all at the positive direction of Y axis. The original distance between the coil and the particles are 0.815mm (H1), 0.565mm (H2), 0.315mm (H3) and 0.065mm (H4) separately at the entrance of the pipe.

When debris releases from the entrance, it tends to flow to the center place of pipe where the oil velocity is larger than that at the former position. When metal debris passes through the micro coil, the distance between debris and the micro coil will increase. The increase of the distance is different while the position of debris in pipe is not the same. From the simulation, it can be seen that the change of H1 is -0.059mm and the change of H3 is 0.064mm as comparing the highest position when it passes though the micro coil with the original position of the debris. H2 and H4 also changes with different value. These changes indicate that the trace of debris relates to the time the debris flows in pipe and the impediment of micro coil. Also, the property of oil and the size of pipe bear on the trace of debris.

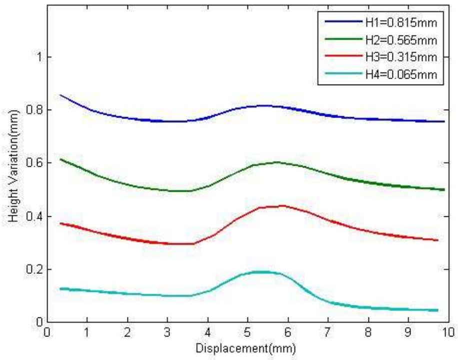


Fig. 9：The traces of debris with different position

The trace of metal debris is studied in the simulation preliminarily. This work is beneficial for obtaining the distribution of debris when it flows through the coil. The distribution and the size of debris relate to the inductive signal. Therefore, according to the clear distribution, the relationship between the changing rate of coil's inductance and the size of debris can be obtained in future work.

CONCLUSION

The micro inductive sensor with a good sensitivity is made in this paper by studying the former research of the optimization. This sensor is deposited into pipe to detect the flowing metal debris. The method is propitious to detect more sample oil than other inductive sensor. The sensor has the ability to detect the debris with the size from 88µm to 100µm, which is suitable for monitoring the machinery. The software of Comsol is used to build a simulation model to study the trace of debris. The simulation indicates that the distance between debris and the coil will increase when it flows through the coil. According to the simulation result, the distribution of debris in pipe can be studied. Through the distribution, the size of debris can be connected to the changing inductance signal. So the size of debris can be obtained at last. These researches have reference value for actualizing the on-line test of metal debris with micro inductive sensor and monitoring the machinery.

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