Study on a High Sensitive Online Sensor for Wear Particles in Lubricant

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Abstract. On-line condition monitoring reflects the condition of mechanical equipment, which designs to avoid unnecessary detection and discover serious accidents timely. This paper proposes a short solenoid inductance sensor for monitoring the metal abrasive particles in lubricant within internal combustion engine. The mathematical model of sensor is established to analyse the influence of different metal abrasive particles on the magnetic field. In the actual tests, when the particle passes through the specific magnetic field, the signal of the induced electromotive force is converted into a signal frequency which is convenient to detect. The results of the experiments show that the sensor could effectively detect iron particles of 50μm in size and copper particles of 100μm in size, which means this short solenoid inductance sensor is effective in monitoring the internal combustion engine online.

1. Introduction

Friction and wear exist in all rotating and reciprocating machines, which inevitably cause mechanical failure in the long-time operation. Therefore, condition monitoring is fundamental in regular equipment maintenance. On-line monitoring not only avoids unnecessary shutdown for inspection, but can also provide an early warning before failure occurs, which can maximize the machine operation efficiency[1].

In the continuous improvement process for internal combustion engine technology, the reliability requirements of internal combustion engines have become higher. As a result, timely state detection and fault diagnosis of internal combustion engines is particularly important. During the operation of internal combustion engines, the lubricating oil is continuously contaminated. The main causes of oil contamination are moisture, intrusion of outside impurities, high temperatures, high shear effects and formation of solid abrasive particles. According to the statistics for mechanical equipment such as internal combustion engines, 70%-80% of equipment failures are caused by contamination of the lubricating oil, 80% of which are caused by solid abrasive contaminants[2]. Among these failures, the metal abrasive particles are in direct contact with the surfaces of the moving parts in the internal combustion engine and have a major impact on the wear of the engine.

It can be seen that metal abrasive particles are closely linked to the internal combustion engine, and information about the operating conditions of the internal combustion engine can be inferred from the metal abrasive particles. From the results of the detection of metal abrasive particles in the lubricating oil, the wear condition of the internal combustion engine can be deduced[3], thereby providing an early warning of the condition of an internal combustion engine and allowing for targeted maintenance. Therefore, lubricating oil wear detection...
technology can be used as an important method for condition monitoring and fault diagnosis of an internal combustion engine[4].

At present, a variety of lubricating oil liquid on-line monitoring technologies have been developed, including capacitive[5], inductive[6], acoustic[7] and optical[8] sensors. Among these methods, inductive sensors have excellent prospects for monitoring metal wear due to their simple structure, low cost, ability to resolve magnetic metals and non-magnetic metal particles[9]. Magnetic collection sensors can remove high-flux magnetic metal particles, but are unable to distinguish magnetic from non-magnetic metals[10]. Three-dimensional electromagnetic structures, such as MetalSCAN sensor, can detect particles in the size range above 100μm, and is able to distinguish magnetic from non-magnetic particles. But this sensor is of high price, which limits its application. Similar sensors have high requirements for structural symmetry. Abnormal wear has already appeared when an engine starts to produce particles of 50-100μm[11]. Therefore it is very important to develop a cheap and reliable sensor.

A short solenoid inductance sensor using an electromagnetic structure is designed in this article. Through simulating the electromotive force induced when the abrasive particles pass through the sensor, the influence of different particles is identified. The results from the simulation are compared with the experimental results, which confirms the effectiveness of the proposed method.

2. Sensor design

Figure 1 illustrates the sensing mechanism of the wear particle sensor. The process of the metal particle passing through a metal coil will cause a change in the magnetic flux of the coil. The magnetic flux variation will inevitably change the inductance of the coil. The magnetic particles strengthen the magnetic field when passing through it, so that the inductance value of the coil increases. The non-magnetic particles have the opposite effect, which decreases the inductance of the coil. Therefore, the different types of metal particles can be detected by identifying different inductance. Size, numbers and other information about the particles can be obtained by measuring the magnitude of the change.

Figure 2 shows the design of sensor, which consists of: fluidic channel of 1.0 mm in inner diameter and a 2-layer, 20-turn planar coil wrapped around the fluidic channel. Considering the small amplitude of the detection signal caused by the metal particles, the smaller the inner diameter of the sensor solenoid is, the more able it is to capture the signal. Therefore, the inner diameter should be set as small as possible without affecting the metal particles passing through it. The purpose of this paper was to detect metal particles in the range of 0~400 μm, the inner diameter of the sensor was set to 1mm. The time for particles to pass through the sensor is very short, which can reduce the interference of outside signals on the detected signal. As shown in figure 2, the coil works as an inductance, \( L \), in serial with a resistance, \( R \), an external capacitor, \( C \), was connected to the coil in parallel to form a parallel \( L-C-R \) resonant circuit.
Figure 2. Design of the sensor

When the capacitance $C_p$ is constant, a change in the frequency is only caused by the change in the inductance. Eq. (1) can be satisfied, in which,

$$k = \frac{1}{2\pi\sqrt{C}}.$$  

$$\Delta f = f_2 - f_1 = \frac{1}{2\pi\sqrt{(L+\Delta L)C}} - \frac{1}{2\pi\sqrt{LC}} = k \frac{\sqrt{L} - \sqrt{L+\Delta L}}{\sqrt{L(L+\Delta L)}}$$  

To simplify the expression, make $\epsilon = \frac{f_2 - f_1}{f_1}$, and Eq. (2) is achieved, in which,

$$\epsilon = -\frac{1}{\sqrt{1 + \epsilon_i}}$$  

By measuring the rate of the change in frequency $\epsilon$, the particles can be detected. According to the positive or negative of $\epsilon$, the different types of metal abrasives can be distinguished. From the Eq. (2), the rate $\epsilon$ is related to the size of the metal wear particles. When the other parameters are fixed, the size of the metal particle can be ascertained by the amplitude from the rate of the change in frequency. The rate $\epsilon$ forms a corresponding relationship with the size of the metal particles, thus allowing for the measurement of the size of these particles.

3. Simulation calculations

When the metal particles pass through the sensor, the magnetic field is constantly changing due to the disturbance caused by the metal particles. In this paper, the transient magnetic field simulation is carried out to monitor the real time change. The cross-section of the band is set to a 24-sided cylinder with a radius of 0.45mm, and the height is set to 5mm. The metal particles, simplified as cubes, moving in the band are chosen to be a certain length (0-400μm). The solution region is set as a cylinder with a radius of 0.8 mm and a height of 6 mm.

3.1. Simulation result

The size of the particles produced in an internal combustion engine is mostly concentrated in the range of 0 to 400μm. In the transient simulation model, particles with an edge length of 0-400μm are simulated at intervals of 50μm. During the process of the particles moving through the magnetic field of the sensor, the metal particles cause the magnetic flux of the coil to change, and then generate an
induced electromotive force $E$. The electromotive force $E$ induced by the iron particles of various sizes is shown in Figure 3.

From the figure of iron particles, the induced electromotive force $E$ is sinusoidal throughout the entire process. According to the peak of each curve for different size, the change range caused by the iron abrasive particles of 50~400μm in size increase from 6.4074nV to 2147.9nV. The induced electromotive force $E$ caused by each different size of the copper particles is shown in figure 4 (b). Unlike the iron particles, when the copper particles pass through the sensor, a valley and a peak successively appear in the graph of the induced electromotive force, displaying a cosine curve. From the point where the induced electromotive force reaches a peak, the induced electromotive force for the 50~400μm copper particles is 3.3248~624.6160nV, which is smaller than the force produced by the same size of iron particles.

4. Experiments on the sensor

4.1. Design of the measurement setup

The wear particle sensor measurement setup consists of a sensor, a detection circuit, a frequency meter, a computer and a stable voltage power supply, as shown in Figure 4. By clamping the inert tube with a special fixture, when metal particle samples passing through the sensor solenoid at a certain speed, the frequency signal waveform and frequency data of the samples can be obtained. The frequency data are processed as a waveform form in Figure 5.
4.2. Experiments on particles

An experimental study is carried out on the iron and copper particles with a size of 50-400 µm. The results of the tests for each size of particle are shown in Figure 6.
Figure 6 (a) shows the test results for iron abrasive particles. The tests for each size of iron particles show that the fluctuation in the rate of change in the frequency caused by the abrasive particles of the same size are in the allowable range. For the iron particles with the size interval of 50μm, the rate of the change in frequency does not intersect. Each range of the rate error corresponds to the respective sizes. The fluctuation indicated that the sensor can distinguish between the iron particles of different sizes and achieve a certain stability.

In the tests of copper particles, it is found that the sensor designed in this paper has difficulty capturing the signal of the 50μm copper abrasive particles. This is because the magnetic field fluctuation caused by the 50 μm copper abrasive particles is very small, and is completely lost in the noise signal. Therefore, in this paper, the copper abrasive particles of the size of 100μm-400μm are tested, and the copper abrasive particles of each size are measured five times, and the average value of the rate of change in frequency is analysed. From Figure 6 (b), it can be seen that when the copper particles pass through the sensor, the detection signal waveform displays a certain amplitude wave peak, that is, the copper particle increases the output frequency of the sensor. As shown in Figure 6 (b), the sensor still shows good stability for the detection of copper particles of the same size during the copper particles test. For copper particles with a size interval of 50μm, the rate of the change in frequency of the sensor output does not show a tendency to intersect. It comes that the sensor is able to distinguish copper particles with different sizes from 100μm to 400μm and have a certain stability.

Figure 7. Comparison between experimental and simulation results of frequency change rate

The experimental results and the simulation results of the frequency variation caused by the iron particles of each size are shown in Figure 7 (a). In Figure 7 (a), the overall relative error of the two results are 1.1529%-3.7431%. The maximum relative error is in the test of 150μm iron abrasive particles, and the minimum relative error is in the test of 200μm iron abrasive particles. Considering that an iron particle of 200μm is the key point of the sensor model and simulation, it comes that the sensor is very accurate in the detection of iron particles. The results caused by various sizes of copper particles are displayed in Figure 7 (b). The overall relative error of the two sets of results are between 2.7491% and 7.3904%, and the relative error decreases with the increase of the size of the copper particles in the range of 100μm-200μm. The minimum relative error is appeared at 200μm for the copper particles, and the maximum relative error was at 100μm for the copper particles. Compared with the test of the iron particles, the relative error of the test of the copper particles is large, so it is obvious the sensor is not as accurate when detecting the copper particles as when detecting the iron particles. Considering that the larger sized particles in the range of 150-300 μm are more deleterious
for an internal combustion engine, the relative error of 2.7491%-4.4534% is acceptable. This means that the sensor can be used in the detection of copper particles.

5. Conclusion
In this paper, the transient simulation of the magnetic field of a sensor is studied through using the finite element analysis method, and the influence of the metal abrasive particles size affecting the sensor magnetic field is studied. The detection performance of the sensor is verified by constructing the sensor equipment and testing metal particles of different sizes. The simulation of the different sizes of metal abrasive particles shows that the induced electromotive force caused by the iron abrasive particles is $6.4074-2147.9nV$. The frequency change rate of the iron particles is $0.3694%-0.001109\%$. The induced electromotive force of the sensor caused by the copper particles is $3.3248-624.6160nV$. And the frequency change rate of the copper particles is $0.0005751%-0.1029\%$. Through the tests of the metal particles, the recognition curve of the sensor is obtained and plotted, and the simulation data are compared with the experimental results. And the error is analysed likewise. The experiments carried out in this paper prove that this online sensor could effectively identify the metal particles, which is effective in internal combustion engine wear monitoring.

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