Design of electromagnetic sensor for metal wear particle detection in oil

Yunbo Zuo, Yuhai Gu, Yanhai Zhang

Abstract: Wear is one of the common faults in the mechanical transmission system. Detection of wear particles in lubricating oil can detect and evaluate the wear degree of mechanical equipment. The electromagnetic sensor for metal wear particle detection can be connected in series with the oil circuit, which has the advantages of full liquid flow, simple structure, distinguishing metal properties, and not being influenced by bubbles and vibration. In view of the shortcomings of the existing electromagnetic sensor for wear particle detection, the detection principle and the induction electromotive force model were studied, and the magnetic field change of the metal particles through three coil differential solenoids was analysed. The optimisation design method was proposed here, which was about the related parameters, such as the wire diameter, the coil turns, the coil widths and so on. The experimental analysis of the sensor was carried out based on detection hardware system that could provide the phase-locked amplification function. The 10-mm inner diameter sensor could detect the minimum 100-μm ferromagnetic metal abrasive particles after optimisation. The developed sensor could provide data information for the abrasive particle detection, fault diagnosis and early warning of wear degree of mechanical equipment.

1 Introduction

The lubricating oil can reduce the wear and working temperature of the mechanical transmission system. Detecting the metal wear particle information in lubricating oil can reflect the wear state of the transmission system and prevent serious wear failures. The methods of detecting metal particles in oil include optical detection, electromagnetic detection, and ultrasonic detection. The detection accuracy is high, but it cannot distinguish metal properties and it can be influenced by bubbles. The ultrasonic detection accuracy is not high, and ultrasound can easily destroy particles, resulting in re-contamination of oil products. The electromagnetic detection has simple structure, fast response speed, and is not susceptible to vibration, air bubbles, and other external disturbances [1–3]. The optical detection and the ultrasonic detection are often offline detection, and their results are lagging behind. The electromagnetic detection has become one of the important research directions of online oil particle detection. The electromagnetic type sensors developed abroad include Canadian GasTOPS MetaSCAN, American MACOM Techalerrttm10 and so on. The domestic research institutes include National University of Defence Technology, Beijing Institute of Technology, Beijing Information Science and Technology University, Beijing Jiaotong University, Yanshan University, China Aerospace Science and Technology Group and so on [4–6]. At present, the detection stability and accuracy of domestic sensors are inferior to similar products abroad. So, aiming at the design difficulty of electromagnetic metal wear particle detection sensor, the characteristics of the magnetic field of the sensor were analysed, and the optimisation design method of the sensor structure parameters was put forward here, which could improve the detection precision of the sensor.

2 Magnetic field analysis of electromagnetic differential sensor for metal wear particle detection

2.1 Principle analysis

The differential electromagnetic sensor for metal wear particle detection mainly consists of the shell, the capacitance, the two excitation coils, and one induction coil. The excitation coils and capacitance can form LC oscillating circuits, receive sinusoidal signals from external input, and produce two dynamic oscillating magnetic fields of the same size and opposite magnetic polarity. The two magnetic fields, respectively, act on the induction coil in the middle. If the magnetic fields generated by the two excitation coils are completely symmetrical, the magnetic field of the induction coil at the midpoint is completely counteracted and the induced electromotive force is zero. When the metal particles pass through the central pipe of the coil, the central permeability of the excitation coil is changed, which makes the induction coil have the magnetic flux change and produce the induction electromotive force output. The magnitude and phase of the induced electromotive force reflect the size, speed, and ferromagnetic properties of the metal particles passing through the central line of the magnetic field. The schematic diagram of the three coils is shown in Fig. 1. The generated signal schematic diagram is shown in Fig. 2. The sensor will be fixed in series with the oil circuit. In order to prevent interference from the external environment of the inductive signal, it is necessary to install metal shield shell outside of the coils.

2.2 Magnetic field analysis

The excitation coil is a hollow solenoid made of copper enamelled wire. Therefore, the magnetic field on the axis of a circular conductor can be analysed first. Based on the Biot–Savart Law, which is the magnetic field theorem of any point near the finite length of a straight wire, the model of the axis magnetic field of a single circular conductor is established as shown in Fig. 3. Suppose
In the above formulas, $dB$ of the point $P$ on the axis is calculated as Formula (1). The angle between the $dB$ and central axis is $\alpha$, and the $\beta$ is the residual angle of the central axis. The magnetic field $B$ on the axis is coplanar with the central axis and is shown in Formula (2)\[7–9].

$$dB = \frac{\mu_0 Idl}{4\pi r}$$

(1)

$$B_s(x,t) = \frac{\mu_0 IN}{4L} \left( \frac{x + L}{\sqrt{R^2 + (x + L)^2}} - \frac{x - L}{\sqrt{R^2 + (x - L)^2}} \right)$$

(2)

In the above formulas, $B$ is the intensity of magnetic field, $I$ is the value of exciting current, $\mu_0$ is the air permeability, $N$ is the exciting coil turns, $R$ is the coil radius, $L$ is an half of the coil length, and $x$ is the distance from coil centre in length direction.

The magnetic field of the sensor is formed based on the two-dimensional model of the coil as shown in Fig. 4. The magnetostatic density diagram is shown in Fig. 5. The sensor shell is made of stainless steel.

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Considering about the particle movement in the alternating magnetic field of the sensor, we cannot ignore the weakening effect of the eddy-current effect on the external magnetic field. Therefore, it is necessary to establish the model of the magnetic properties of the abrasive particles in the alternating magnetic field and study the magnetic field of the ferromagnetic particles in the alternating magnetic field. The relation between the internal and external magnetic fields of the magnetic field is shown in Formula (5) and Formula (6).

$\mu_i H_i = B_i - \frac{1}{2} \mu_i M$

(5)

$B_i = B_0 + \frac{2}{3} \mu_i M$

(6)

where, $B_0$ and $B_1$ are magnetic induction intensity inside and outside of particles, respectively, $M$ is the particle magnetisation, $H_0$ is the magnetic intensity inside of particles, $\mu_i$ is the material permeability. Therefore, the magnetisation effect can make the magnetic field distribute uniformly in ferromagnetic particles, and the internal magnetic induction intensity is shown in Formula (7).

$$B_i = \begin{cases} \frac{3}{\mu_i + 2\mu_0} B_s, & B_i < B_s \\ B_0 + 2B_s, & B_i > B_s \end{cases}$$

(7)

The $B_s$ is the saturated magnetic induction intensity of the material. When the spherical particles do not reach magnetic saturation, the total magnetic flux change caused by magnetisation is $\Delta \phi_1$ as shown in Formula (8) and the induction electromotive force $E$ is shown in Formula (9).

$$\Delta \phi_1 = 2\lambda B_1 \frac{4\pi}{3} R_0^3$$

(8)

$$E = j\omega \mu \omega \int \frac{10NN_0R_0^3}{(R^2 + x^2)^{3/2}} (\mu - \mu_0)$$

(9)

where, $R$, $N$, $\mu_0$, and $x$ are same as above Formula (2), $N_0$ is the induction coil turns, $R_0$ is the particle radius, $j$ is the complex variable, $f$ is the exciting frequency, and $\mu_1$ is the particle permeability.

2.3 Magnetic field simulation

The magnetic field simulation software JMAG was used to analyse the magnetic field changes of particles passing through the centre of the magnetic field. The magnetostatic density diagrams of the two-dimensional model of the coil are shown in Fig. 4. The simulation analysis models of wear particles in different locations were established, and the transient changes of induction voltage were obtained. The position of the abrasive particle is shown in the circle in the picture.

3 Structure and parameter optimisation

According to the actual application requirement, the sensors need to be connected to the oil circuit in series, shield the external magnetic field and other interference. The structure of the sensor is designed as shown in Fig. 6. The sensor shell is made of stainless steel.
The oil pipeline (the following analysis is all based on the 10 mm diameter of the aviation plug is determined, the size of the shell is interface is welded. Therefore, the optimisation of the structural parameters of the sensor mainly takes into account the inner diameter of the skeleton). Therefore, the optimisation of the optimal design of the diameter, turns, gaps, and widths of the coil.

### 3.1 Determination of the wire diameter

The wire diameter size of the coil should not be too big or too small. With the increase of wire diameter, the turns of the same coil width will decrease and the ratio of induced current amplification will decrease. When the wire diameter decreases, the coil resistance will increase if the number of turns is same. When the excitation voltage is constant, the induced current will decrease. Experimental analysis was carried out on line diameter 0.1, 0.15, 0.2, 0.25, and 0.3 mm. When the wire diameter was 0.1 mm, the difficulty of wire welding was increased and the probability of breakage increased. Through experimental experience, the coil diameter of 0.2 mm is the best, and the output voltage is the largest under the same other structural parameters.

### 3.2 Determination of the gap between coils

The coil gaps of the sensor have an important influence on the performance and accuracy of the detection. When changing the theoretical mathematical model, we only need to change the gap size \( w \). To keep the boundary constraints and other working parameters constant, the simulation of the ferromagnetic metal wear particles with a diameter of 100 μm was carried out when passing through a different gap size sensor with 1 m/s velocity. From the diagram below, we can see that the induced voltage value without amplification decreases with the continuous increase of gap \( w \), and the induction voltage reaches the maximum value at \( w = 2 \text{ mm} \) (Fig. 6).

### 3.3 Determination of the coil width

The coil width directly affects the resolution of two wear particles passing through the central pipeline. If the width of the coil increases, the distinguished distance between two particles will increase. When the coil width is reduced and the wire diameter is constant, the coil height (or outer diameter of the coil) will increase with the same number of coil turns, and the induction intensity of the magnetic field centre will decrease. At the same time, the processing technology is limited to select the width \( b = 2 \text{ mm} \) as the best, which is convenient to process and ensure the outer diameter of the coil is small and which will not weaken the induction magnetic field.

### 3.4 Determination of the coil turns

The wire diameter, the coil width, and the exciting coil turns are directly affected by the oscillation frequency of the excitation circuit. Therefore, the inductance of the circuit is calculated using the Formula (10) in the condition of determining the oscillation frequency and capacitance of the circuit, and then the coil turns are calculated according to the Formula (11) \[10–12\]. The induction coil turns are selected according to the principle of appropriate voltage amplification. According to the theoretical analysis of the coil turns and the actual coil winding effect, the coil parameters are determined as shown in Table 1.

\[
f = \frac{1}{2\sqrt{LC}} \quad (10)
\]

\[
L = \frac{\pi R^2 \mu_0 N^2}{b} \quad (11)
\]

In the above formulas, \( f \) is exciting frequency 24.68 KHz. \( L \) is the parallel inductance value and \( C \) was matching capacitance. \( R, N \) and \( \mu_0 \) are same as above Formula (2) and \( b \) is the coil width.

When the structural parameters of the sensor are determined, the electromotive force of the induction coil has a linear increase with the velocity of the wear particles, has a non-linear increase with the permeability of the abrasive particles, and has a non-linear increase with the radius of the abrasive particles. Therefore, the relationship between the voltage output of the sensor and the radius of the abrasive particle needs to be calibrated by a lot of experiments.

### 4 Experimental analysis

In order to verify the detection performance of the designed sensor, the experiments of inductive sensor were carried out without lubricating oil. As shown in Fig. 7, the test required the ferromagnetic wear particles of different sizes, such as 100, 200, and 300 μm. They were loaded into the heat shrinkable tube, and then the heat shrinkable tube was inserted in the sensor pipe by the hand. The characteristics of the wave form were observed on the interface of the developed scanning analysis system (Fig. 8). The waveform of induction electromotive force are shown in Figs. 9–11. From the diagrams, it can be seen that the 10-mm inner diameter sensor after optimisation can detect the minimum diameter of 100-μm ferromagnetic abrasive particles, but the corresponding magnetic field effect is weak; however, the
corresponding signal waveforms of 200 and 300-μm diameter abrasive particles are clear.

5 Conclusion

The electromagnetic sensor for metal abrasion detection can quickly detect the quantity and size of metal particles in lubricating oil, which can reflect the wear degree of the mechanical equipment. After optimising the wire diameter, coil widths, coil gaps, and coil turns, the 10-mm coil inner diameter sensor can detect the ferromagnetic abrasive particles of 100 μm. It has improved the detection precision, and it can provide the research conditions for the wear-state analysis, the fault diagnosis and early warning of mechanical equipment. However, when the non-ferromagnetic metal particles pass through the magnetic field, the magnetisation effect is poor and the output voltage of the sensor decreases. The sensor shell with poor eddy-current effect but strong magnetic shielding effect should be chosen to further improve the detection ability of the sensor.

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7 References

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