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Study of the Sensor for On-line Lubricating Oil Debris Monitoring

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Abstract: Mechanical parts such as gears and bearings used in mechanical equipment have a finite lifetime because of corrosion and wear. If the parts are in abnormal operation and is not detected, it may cause catastrophic component failure during operation. One effective approach to detect signs of potential failure of the mechanical equipment is to examine the debris particles in its lubricating oil. This article presented an inductive debris sensor which is designed on the basis of the principle of inductance balance. The structure design and the principle of it are studied. The intensity distribution of its magnetic induction is simulated by the use of simulation software Ansoft Maxwell. The mathematical model when there is a debris particle passing through the sensor is analyzed and the characteristics of the sensor's induction signal is gotten. Experiments have shown that debris particles can be detected by this sensor. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Inductive sensor, Debris detection, Magnetic induction intensity distribution, Mathematical model.

1. Introduction

Mechanical parts such as gears and bearings used in mechanical equipment have a finite lifetime because of corrosion and wear. If the parts are in abnormal operation and is not detected, it may cause catastrophic component failure during operation [1]. One effective approach to detect signs of potential failure of the mechanical equipment is to examine the debris particles in its lubricating oil. During normal machine operation, the size of wear debris in lubricating oil is typically in the range of 10 um to 20 um. When abnormal wear begins, the size of the debris particles grows as large as 50 um to 100 um. The concentration and size of particles increase gradually with time, until the machine fails [2]. Thus, continuous monitoring of wear debris in lubrication oil is critical to avoid catastrophic system failure of machines [3]. Tribological surfaces are often coated with special nonferrous metallic coating to reduce contact friction. Thus, the ability to differentiate ferrous and nonferrous metallic debris in the lubrication oil is important [1].

A few on-line oil condition monitoring methods have been developed, including optical scattering counters [4-5], acoustic emission detection [4, 6], capacitance sensing [7-8] and magnetic inductive debris sensors. The advantages and disadvantages of these methods have been reviewed in article [1]. The magnetic inductive method is based on the principle of electromagnetic induction, in addition to their low cost and low maintenance cost, inductive debris detectors can differentiate between ferrous and non-ferrous debris and have no response to air bubbles

[9]. According to the amount of inductive coil in sensors, inductive debris detectors can be divided into three kinds. The sensors have one coil or two coils in it are susceptible to external influences, so their most significant disadvantage is low sensitivity [10-11]. The sensor which has three coils in it is designed on the basis of the principle of inductance balance. The magnetic field of the sensor's detecting coil is in dynamic equilibrium, so that the sensor is free from environmental impact [12]. Furthermore, it has high measuring accuracy.

This article presented an inductive debris sensor which has three coils. The structure design and the principle of it are studied. The intensity distribution of its magnetic induction is simulated by the use of simulation software Ansoft Maxwell. The mathematical model when there is a debris particle passing through the sensor is analyzed and the characteristics of the sensor's induction signal is gotten. Experiments have shown that debris particles can be detected by this sensor.

2. Sensor Design

This sensor is designed based on the principle of electromagnetic induction. The sensor module contains the working elements of the sensor in a welded stainless steel housing designed to minimize exposure of the coils to distortion due to external factors. The magnetic coil assembly consists of three coils which surround a magnetically inert section of tubing. The two exciting coils are on separate sides of the tubing, the detecting coil is in the middle. The tube has three grooves to fasten the magnetic coils and it allows the entire oil flow to pass without obstruction. The structure diagram of the sensor is shown in Fig. 1.

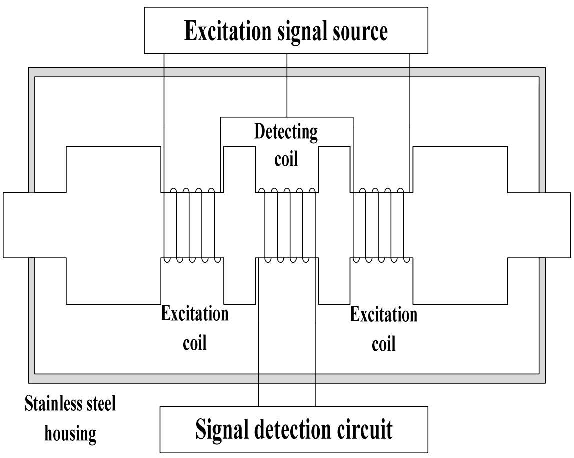


Fig. 1. Structure diagram of the sensor.

Two drive signals are applied to the outside exciting coils. The two drive signals have same frequency, their phase and amplitude are adjustable. In the ideal situation, the respective magnetic fields of the two outside exciting coils are opposed and cancel each other just under the center sense coil. But because of the phase and amplitude resolution of the drive signals and the processing technique of the sensor are confining, it is impossible for the two magnetic fields to cancel each other just under the detecting coil. So, there is a carrier signal which has the same frequency with the drive signals outputted by the detecting coil.

The induction signal caused by the debris particle will modulate on the carrier signal through amplitude modulation when it passes through the sensor. The amplitude of the induction signal is in direct proportion to the size of the debris particle; the frequency of the induction signal is in direct proportion to the speed of the debris particle; the phase of the induction signal for ferrous debris particle is opposite that of non-ferrous so that this sensor can differentiate ferrous and non-ferrous debris particles.

3. Simulation of the Sensor's Magnetic Field Distribution

The intensity distribution of the sensor's magnetic induction is simulated by the use of simulation software Ansoft Maxwell.

The 3D model of the sensor is shown in Fig. 2.

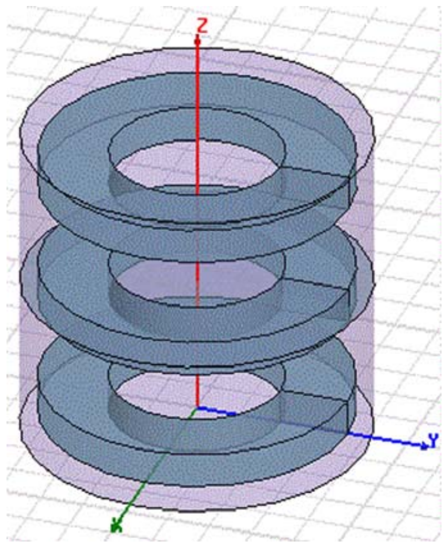


Fig. 2. 3D model of the sensor.

Fig. 3 is the excitation current which is used as the exciting coil's drive signal. Choose time point m1 and m2 as the investigated points, the current intensity reaches the peak value at m1, and it turns zero at m2. Because of the magnetic induction intensity is in direct proportion to the current intensity, the magnetic induction intensity of the exciting coil is biggest at m1 but smallest at m2.

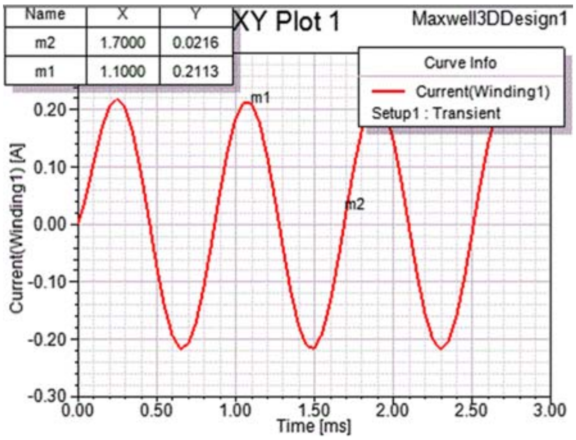
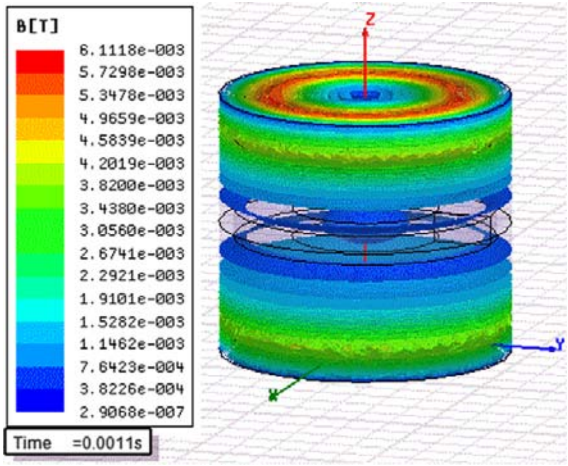
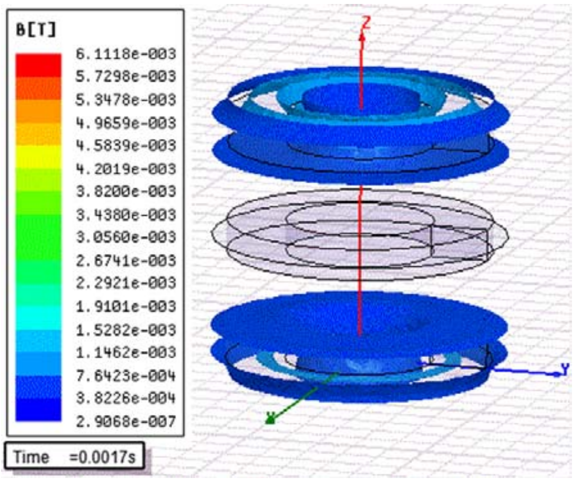


Fig. 3. The excitation current which is used as the exciting coil's drive signal.

The simulation result is show in Fig. 4 and Fig. 5. Fig. 4(a) and Fig. 5(a) is the simulation result at m1, Fig. 4(b) and Fig. 5(b) is the simulation result at m2.

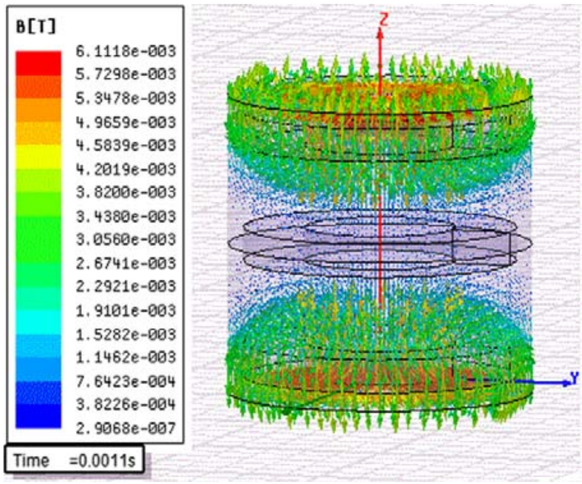


(a)

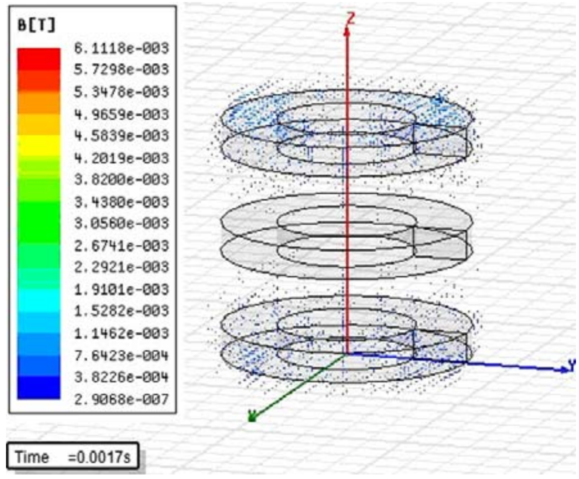


(b)

Fig. 4. Intensity distribution of the sensor's magnetic induction (scalar field).



(a)



(b)

Fig. 5. Intensity distribution of the sensor's magnetic induction (vector field).

From the simulation result we know that the magnetic induction intensity is not evenly distributed. The magnetic induction intensity at the area close to the exciting coil is bigger than what it is at the centre of the exciting coil. The respective magnetic fields of the two outside exciting coils are opposed and cancel each other just under the center sense coil (in the ideal situation).

4. Mathematical Model of the Magnetic Field Distribution

The balance of the magnetic field at the detecting coil will be break while a debris particle is passing through the sensor.

As is shown in Fig. 6, the debris particle will be magnetized when it is passing through the first exciting coil. A demagnetizing field will appear in the particle [13].

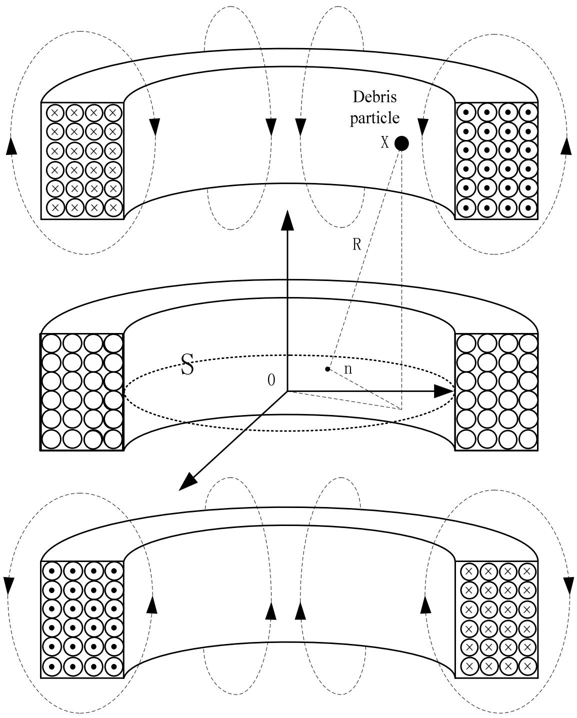


Fig. 6. Debris particle passing through the sensor.

Suppose the debris particle is at point X, the magnetic field intensity of the debris particle is

$$H_i = -NM \tag{1}$$

where M is the magnetization intensity of the particle; N is the demagnetizing factor of the particle.

The total magnetic field intensity inside the debris particle is

$$H = H_i + H_o = H_o - NM \tag{2}$$

H_o is the magnetic field intensity of the exciting coil at point X.

The magnetization intensity M is in direct proportion to the total magnetic field intensity H for isotropic magnetic medium, so

$$M = \chi_m H \tag{3}$$

χ_m is the magnetic susceptibility of the magnetic medium in Eq. 3.

With Eq. 2 and Eq. 3, we get Eq. 4.

$$M = \frac{H_o \chi_m}{1 + N\chi_m} \tag{4}$$

From the definition of the magnetic field intensity H, we know that

$$H = \frac{B}{\mu_0} - M \tag{5}$$

With the help of Eq. 3 and Eq. 5, the magnetic induction intensity inside the debris particle can express as Eq. 6.

$$\begin{aligned} B_i &= \mu_0 (1 + \chi_m) H \\ &= \mu_0 \mu_r \frac{M}{\chi_m} = \mu_0 \mu_r \frac{H_0}{1 + N\chi_m} \end{aligned} \tag{6}$$

where $\mu_r = 1 + \chi_m$ is the relative permeability of the particle.

From Eq. 6 we know that the particle's magnetic induction intensity B_i is in direct proportion to its permeability μ_r but in inverse proportion to its demagnetizing factor N and magnetic susceptibility χ_m.

As is shown in Fig. 4, point n is an arbitrary point in plane S just under the detecting coil. The magnetic induction intensity of the particle at this point is K_n times smaller than what it is at point X. Suppose the original magnetic induction intensity at point n is B_{osn}. So the total magnetic induction intensity at this point is

$$B_{sn} = B_{osn} + K_n B_i = B_{osn} + \Delta B_n \tag{7}$$

The value of B_{osn} is related to the position of point n, the value of K_n is related to the distance between the debris particle and point n.

From Eq. 7 we know that the magnetic flux penetrates plane S is more than before, so we get Eq. 8 (only the vertical component of the magnetic induction intensity can effect the magnetic flux).

$$\begin{aligned} \Phi_s &= \int_s (B_{sn})_z ds = \int_s (B_{osn})_z ds + \int_s (\Delta B_n)_z ds \\ &= \int_s (B_{osn})_z ds + \int_s (K_n B_i)_z ds = \Phi_{os} + \Delta\Phi \end{aligned} \tag{8}$$

Suppose that the detecting coil consists of m planes just like S. The total flux linkage of the detecting coil is

$$\begin{aligned} \Psi &= \sum_{i=1}^{m} \Phi_{si} = \sum_{i=1}^{m} (\Phi_{os} + \Delta\Phi) \\ &= \sum_{i=1}^{m} \int_s (B_{osn})_z ds + \sum_{i=1}^{m} \int_s (K_n B_i)_z ds \\ &= \Psi_o + \Delta\Psi \end{aligned} \tag{9}$$

The induced electromotive force E of the detecting coil is

$$
\begin{aligned}
E &= -\frac{d\Psi}{dt} = -\frac{d\Psi_o}{dt} - \frac{d\Delta\Psi}{dt} \\
&= -\frac{d\sum_{i=1}^{m}\int_s (B_{osn})_z ds}{dt} - \frac{d\sum_{i=1}^{m}\int_s (K_n B_i)_z ds}{dt} \\
&= E_o + \Delta E
\end{aligned}
\tag{10}
$$

With Eq. 6 and Eq. 10, we known that the induced electromotive force E of the detecting coil can expressed as

$$
\begin{aligned}
E &= -\frac{d\sum_{i=1}^{m}\int_s (B_{osn})_z ds}{dt} - \frac{d\sum_{i=1}^{m}\int_s (K_n \mu_0 \mu_r \frac{M}{\chi_m})_z ds}{dt} \\
&= -\frac{d\sum_{i=1}^{m}\int_s (B_{osn})_z ds}{dt} - \frac{d\sum_{i=1}^{m}\int_s (K_n \mu_0 \mu_r \frac{H_o}{1+N\chi_m})_z ds}{dt}
\end{aligned}
\tag{11}
$$

Because of the field direction of the second exciting coil is opposite that of the first exciting coil, the debris particle will be reversely magnetized when it is passing through the second exciting coil. Another induced electromotive force $\Delta E'$ which the polarity is opposite to ΔE is generated. These two induced electromotive forces change the amplitude of the carrier wave.

If a non-ferrous debris particle is introduced into the sensor, an eddy current is generated inside the particle in a way that opposes the original magnetic field. As a result, the total magnetic flux is decreased. On the otherwise, if a ferrous debris particle is introduced into the sensor, the magnetic flux would be enhanced [14]. So, the induced electromotive forces generated by the detecting coil caused by ferrous and non-ferrous debris particles have opposite polarity. That means the induction signals of ferrous and non-ferrous debris particles are opposite in phase. Fig. 7(a) is the induction signal of ferrous debris particle, Fig. 7(b) is the induction signals of non-ferrous debris particle.

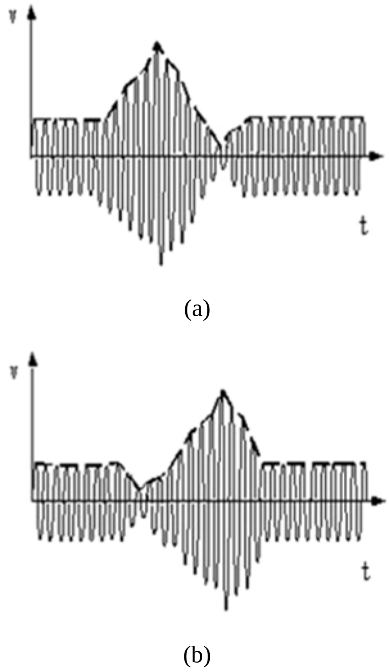


Fig. 7. Induction signals of ferrous and non-ferrous debris particle.

When it comes to practical application, the characteristic signals of ferrous and non-ferrous debris particle is shown in Fig. 8. The left one is the characteristic signal of ferrous debris particle, the right one is the characteristic signal of non-ferrous debris particle.

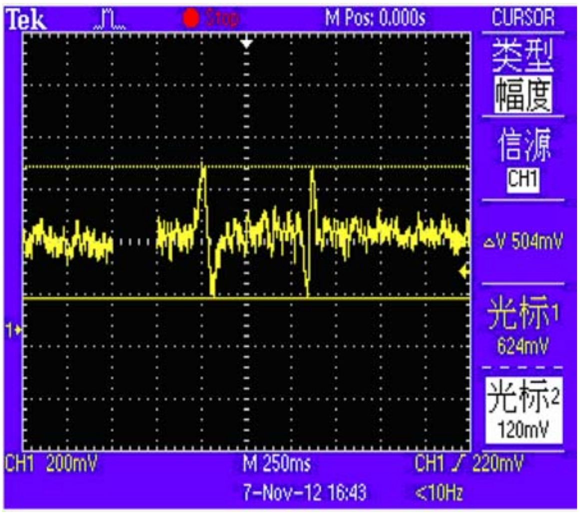


Fig. 8. Induction signals of ferrous and non-ferrous debris particle.

5. Test of the Induction Signals

Taking this sensor as the core, a debris particle detector has been designed. This debris detector is composed of five modules: sensor, excitation signal source, signal detection circuit, DSP (Digital Signal Processor) control circuit and display circuit. The two outside exciting coils of the sensor are driven by the excitation signal source. When there is a debris particle passing through the sensor, the particle's characteristic signal will be detected by the signal detection circuit and then output to the DSP control circuit to analyze. The parameters of the debris particle will be shown on the display circuit.

6. Conclusions

This article presented an inductive sensor for on-line wear debris detection in lubrication oil. The magnetic field distribution of the sensor is analyzed and simulated. When a debris particle is passing through the sensor, its characteristic signal will modulate on the detecting coil's output carrier signal. The amplitude of the characteristic signal is related to the particle's size, permeability and magnetization intensity, the phase of the characteristic signal is effected by the particle's material, the period of the characteristic signal is effected by the particle's speed.

The detector with a sensor which the inner diameter is 25 mm is able to measure ferrous particle as small as 200~300 um and non-ferrous particle as small as 700 um. The detector with a sensor which the inner diameter is 10 mm is able to measure ferrous particle as small as 100 um. This on-line debris detector run stably and has high measuring accuracy, it can be widely used in debris detection.

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