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Radial inductive debris detection sensor and performance analysis

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Abstract
Mechanical systems are prone to wear which can cause catastrophic failure if not detected and corrected in a timely manner. Hence, debris detection (type and concentration) is important for fault diagnosis and life prediction of hydraulic systems. The paper presents a new inductive method for debris detection based on a radial magnetic field. The sensitivity and precision of the instrument can be controlled by an independent parameter, resulting in higher sensitivity and precision. The paper provides a sensor structure and its mathematic model and discusses the features of the method. Finally, it is experimentally verified that the sensor can effectively detect 20 \(\mu\)m thick ferromagnetic debris (sphere equivalent diameter 290 \(\mu\)m) in a 20 mm diameter pipe. Simulation and experiment indicate that the new method has a distinct advantage relative to the traditional method.

Keywords: radial magnetic field, inductive debris sensor, real-time oil monitoring

1. Introduction
Mechanical systems with moving parts continuously wear during their life. Many studies [1–4] indicate that wear is an important cause of mechanical systems’ failure caused by debris generated during the wear process. Real-time oil debris monitoring can be considered an effective method for fault diagnosis and life prediction [5, 6].

At present, there are many particle detection methods such as optical, inductive, capacitance, resistance, ultrasonic and x-ray methods. The principle and characteristics of these methods are presented below.

The principle of optical methods is based on light particle shielding [7–12]. This kind of sensor utilizes a micro flow tube and outside light irradiation. When oil with debris traverses the light, the debris will block the light. This method can easily detect debris below 5 \(\mu\)m; however, oil transparency and air bubbles in oil can influence the detection precision. In addition, the throttling effect of the micro flow tube can also affect its use in high flow conditions. Thus, optical methods are primarily used for off-line particle detection.

Inductive methods [13–19] are based on the principle of magnetic field. When oil with debris flows through the magnetic field, its inductance or inductive voltage will change. With the above information, the inductive method can detect the type of material and density of debris. The inductive method is robust in terms of oil quality and environment.

Capacitor [20] and resistor [21] methods obtain debris information by detecting the capacitance or resistance between two electrodes in the oil. When debris passes through the detector, the electric field will change. Detecting the capacitor and resistor variance can reflect the debris variance indirectly. Since the above methods can cause oil deterioration, the detection accuracy will degenerate with time.

Ultrasonic methods [20] require the placement of an ultrasonic transmitter and receiver in oil. When debris passes, the ultrasonic waves will be scattered and the received signal will change. Although this method can detect debris, the
result is easily influenced by the oil viscosity, flow rate and mechanical vibrations.

The x-ray method [22–24] can excite the light spectrum with high energy x-ray. Detecting the light spectrum can determine the aggregate particle chemistry. This method is characterized by high precision but needs complex equipment.

In comparison with other methods, the advantages of inductive methods are their simple structure, strong anti-jamming, quick response and rich information. As a result these methods are more commonly used in real-time oil debris monitoring. Thus, many studies have been performed on inductive methods and their application in the field. In 1988, Chambers et al [13] designed an inductive sensor with a magnetic collector. This collector can collect debris in a prescribed period of time and then release it altogether as a bigger piece through the sensor, so that the sensitivity can be improved. The condition of the oil can have a significant effect on the collection efficiency; as a result, detection may be an inaccurate reflection of debris generation. In 1990, Flanagan et al [14] presented a new inductive method for the estimation of debris material and size, consisting of a sensor with a single coil. Their experimental device can control debris speed effectively and the experimental result indicates that the sensor can detect debris above 100 μm in size in a glass pipe with a diameter of 6 mm. Miller et al [15] discussed a triple-coil sensor (ODM) which was developed by a Canadian company, Gas Tops. By measuring the inductive voltage, the instrument is able to detect spherical debris above 125 μm in a 1/2” diameter pipe. The magnetic field of this sensor is not uniform; hence, its output can vary significantly depending on the radial location of debris. The correlation studies [25] indicated that the vast majority of debris size produced by mechanical components is 50–100 μm, so it is necessary to design a debris sensor to be more sensitive and detect smaller debris. In order to accomplish that, Du et al presented two high sensitivity sensors which use a single coil and detect debris by measuring inductance [17, 18]. They further improved the sensitivity of these sensors by using the parallel LC resonance method [19]. These improved sensors can detect 20 μm debris and are the most sensitive. Their outstanding performance benefits from using a micro fluidic channel which is 250 μm in height or diameter, so that the sensors’ sensitivity can be greatly improved. However, this channel is so small that it can clog easily, which then leads to failure. In addition, the channel has a substantial throttling effect which renders the sensors inapplicable for high flow rates.

In order to improve the uniformity of the inner magnetic field, increase the sensitivity of the instrument and make the sensor applicable for high flow rate conditions, the authors developed a new inductive method based on a radial magnetic field. The following sections present the sensor design, provide the sensor model, compare the magnetic field between the new method and traditional methods, and present comparison between experimental and analytical result analysis.

![Figure 1. Inductive debris sensor based on radial magnetic field.](image1)

![Figure 2. The effects of debris on the magnetic field.](image2)
2.2. Mathematical model of RDS

Inductive sensors can be divided into three basic structures: single-coil, double-coil and triple-coil, and two basic measuring methods: voltage and inductance. The voltage measuring sensor can be described as

\[ u = N \lim_{\Delta t \to 0} \frac{\Delta \phi}{\Delta t}, \]  

(1)

where \( u \) is the output voltage of the inductive coil, \( N \) is the number of turns of the inductive coil, \( \Delta \phi \) is the magnetic flux variation caused by passing debris and \( \Delta t \) is the corresponding time lag.

The inductance measuring sensor can be described as

\[ \Delta L = \frac{N \Delta \phi}{I}, \]  

(2)

where \( \Delta L \) is the inductance variation of the inductive coil and \( I \) is the current in the inductive coil.

It is obvious that the important issue is how to describe the magnetic flux of the inductive debris sensor. Since the magnetic flux is the magnetic potential effect on the magnetic resistance results, we can establish the equivalent magnetic circuit like the electric circuit shown in figure 3.

In figure 3, the total magnetic resistance between the equipotential surfaces A and B is equal to the resistance in parallel. And the total magnetic resistance in the air gap is \( R_{AB} \), which can be described as each air path resistance in parallel. So the magnetic flux can be described as

\[ \phi_0 = \frac{F}{R_e + R_{AB}} = \frac{F}{R_e + \frac{1}{\sum \frac{1}{r_i}}}, \]  

(3)

where \( F \) is the magnetic potential, \( R_e \) is the magnetic resistance of the iron core, \( R_{AB} \) is the total magnetic resistance in the air gap and \( r_i \) is the magnetic resistance of the \( i \)th air path.

The coordinate system used in this problem is shown in figure 4, where the \( x \) axis is directed along the pipe central axis and the vertical direction is defined as the \( z \) axis.

Suppose the debris moves along the \( x \) axis; the magnetic flux varies when the debris moves to the \( P \)th path at time \( t \) and can be described as

\[ \Delta \phi = \phi_P - \phi_0 \]

\[ = \frac{F}{R_e + R_{AB}} \sum_{i=1}^{n} \left( \frac{1}{r_i} + \frac{1}{r_i} \right) \left( R_e + \frac{1}{\sum_{i=1}^{n} \frac{1}{r_i}} \right), \]

(4)

where \( \phi_P \) is the total magnetic flux when the debris reaches the \( P \)th path, \( \phi_0 \) is the total magnetic flux when the debris is at infinity and \( r_i' \) is the magnetic resistance of the \( P \)th path when the debris reaches the \( P \)th magnetic path.

In this sensor, \( R_e \) is the magnetic resistance of the iron core and \( R_{AB} \) is the magnetic resistance in the air gap, where \( R_e \ll R_{AB} \), resulting in the approximation

\[ \Delta \phi \approx \frac{F (r_P - r_P')}{{r_P'}}, \]

(5)

\[ = \frac{F (r_P - r_P')}{r_P'}. \]

Suppose the debris could be equivalent to a cuboid of size \( \delta_x \times \delta_y \times \delta_z \). Then we know that

\[ r_p = \frac{l_p}{\delta_x \delta_y \delta_z}. \]  

(6)
magnetic cores as lines in the air gap are equivalently generated by a pair of Based on equivalent magnetic core theory, the magnetic field minimum length of the air gap.

Substituting equations (6) and (7) into equation (5), then

\[
\Delta \phi = \frac{F(r'_p - r_p)}{l_p} = \frac{F \left\{ l_p \left[ l_p - \left( 1 - \frac{1}{\mu_r} \right) \delta_s \right] \right\}}{l_p \left[ l_p - \left( 1 - \frac{1}{\mu_r} \right) \delta_s \right]}
\]

Because \( \mu_r > 0 \) and \( l_q \gg \delta_s \), we obtain

\[
\Delta \phi = \frac{F \delta_s \delta_q \mu (\mu_r - 1) \mu_r}{l_p^2}.
\]

Because point \( P \) is arbitrary, we let \( l_p = l(x) \); then

\[
\Delta \phi = \frac{F \delta_s \delta_q \mu (\mu_r - 1) \mu_r}{l(x)^2}.
\]

Substituting equations (14) into (5), and \( F = N_0 I \), we have the sensor’s output

\[
u = N_0 l \delta_s \delta_q \mu (\mu_r - 1) \mu_r \lim_{\Delta t \to 0} \frac{1}{l^2(x) \Delta t} \]

\[
= -2N_0 l \delta_s \delta_q \mu (\mu_r - 1) \frac{l(x)}{l^2(x)} v,
\]

where \( v \) is the debris speed along the \( x \) axis.

2.3. Description of the magnetic path

Based on equivalent magnetic core theory, the magnetic field lines in the air gap are equivalently generated by a pair of magnetic cores as \( S \) and \( S' \) shown in figure 5. Therefore, they can be approximately described as a group of elliptical arcs, whose endpoints are \( S \) and \( S' \).

The distance between \( S \) and \( S' \) can be calculated as

\[
SS' = kl_g,
\]

where \( k \) is the profile parameter of the air gap, and \( l_g \) is the minimum length of the air gap.

So the length of the magnetic field line in the air gap is

\[
l(x) = \int_{TT'} dl = \int_{\beta}^{\pi/2} \sqrt{4x^2 \sin^2 \theta + k^2 l_g^2 \cos^2 \theta} \, d\theta
\]

\[
= \int_{\beta}^{\pi/2} \sqrt{k^2 l_g^2 + (4x^2 - k^2 l_g^2) \sin^2 \theta} \, d\theta,
\]

where \( x \) is the position of the debris along the \( x \) axis and \( \beta \) is the eccentric angle of point \( T \).

3. Comparison of magnetic fields

The major aspects of sensors’ performance are their sensitivity and precision. The maximum error of inductive methods is due to the non-uniform magnetic field. In another word, detection results depend on whether debris moves along the pipe center or pipe edge. Thus, magnetic field uniformity has a great impact on the detection precision of inductive methods.

Traditional inductive methods use an axial magnetic field, whose coil is wound along the pipe shown in figure 6(a), while the radial inductive method presented in this paper is to use a radial magnetic field where the coil is wound along the iron core and the magnetic field is perpendicular to the pipe as shown in figure 6(b).

Applying simulation of the magnetic field, we can obtain two kinds of magnetic field distributions on the \( Z \) axis as shown in figure 7.

It is obvious that the shapes of the magnetic flux distributions are similar for the two kinds of sensors, where the magnetic flux is big at both edges of the pipes and small in the centers. Ideally, the magnetic flux densities are equal with the same radius in the axial magnetic field section as shown in figure 8(a); the magnetic flux densities at the same \( Z \)-coordinates in the radial magnetic field are also equal as shown in figure 8(b). This difference leads to the small gradient
area of the magnetic flux in the radial magnetic field becoming bigger, so the radial magnetic field uniformity is better than the axial one in the same section.

In order to illustrate the advantages of the radial inductive debris sensor, we select the standard deviation of the magnetic flux density in the central section YOZ to estimate its uniformity. The mean magnetic flux density in the axial magnetic field is shown as

$$\bar{B}_A = \frac{\int_0^R 2\pi r B_A(r) \, dr}{\pi R^2},$$

(14)

where $R$ is the internal radius of the pipe and $B_A(r)$ is the radial magnetic distribution function on the Z axis.

Then, the standard deviation of the magnetic flux density is shown as

$$\sigma_A = \sqrt{\int_0^R 2\pi r (B_A(r) - \bar{B}_A)^2 \, dr},$$

(15)

The mean of the magnetic flux density in the radial magnetic field is shown as

$$\bar{B}_R = \frac{\int_0^R 4\sqrt{R^2 - z^2} B_R(z) \, dz}{\pi R^2},$$

(16)

where $B_R(z)$ is the radial magnetic distribution function of the magnetic flux density in the Z axis.

Then, the standard deviation of the magnetic flux density in the radial magnetic field is shown as

$$\sigma_R = \sqrt{\int_0^R 4\sqrt{R^2 - z^2} (B_R(z) - \bar{B}_R)^2 \, dz},$$

(17)

In order to compare the detection results under axial and radial inductive debris sensors, we set the same number of turns of the coil, same drive current and same pipe diameter. Then, we obtain the uniformity comparison results shown in figure 9, in which the red line represents the uniformity under the axial inductive debris sensor and the blue one shows the uniformity under the radial inductive debris sensor. The results indicate that the radial magnetic field is better than the axial magnetic field in uniformity.

It is obvious that increasing the axial length of the coil will improve the axial magnetic field uniformity but reduce the sensor sensitivity due to the reduced mean magnetic field strength. In addition, the mean magnetic strength does not change with the radial length of the coil, as shown in figure 10. On the other hand, the sensor sensitivity and precision can be improved by increasing the number of turns of the coil and iron axial width in the radial inductive debris sensor. So the sensor based on the radial inductive method makes it easier to achieve high sensitivity and precision at the same time.

4. Experiment and analysis

4.1. Experimental rig

The previous experimental installation [7, 12, 13] puts different particles into the oil and detects the debris by counting the debris number. The aforementioned methods make it difficult to get the exact number of the debris by detecting the spatial location. In order to validate the detection result of the radial inductive debris sensor, we put fixed debris in a wax cylinder and drive the wax cylinder along the pipe by an air control system shown in figures 11 and 12.

In this experimental rig, the pipe is an organic glass pipe 20 mm in diameter and 1 mm in thickness. Debris is fixed in a wax cylinder, so that the wax cylinder can make the debris move freely in the pipe. The wax’s permeability is
close to that of air, so the wax cylinder has little impact on the magnetic field and it can be used to fix the debris. An air pump is used to produce high-pressure air, which could push the wax cylinder in the pipe. By this design, the cylinder’s speed could be adjusted by the throttle, and its direction could be changed by the valve. The photoelectric switch is a coupled structure. When the cylinder stays in the photoelectric switch, the infrared will be cut off and the switch’s output will be high, but the output is low under other conditions. Thus, the cylinder’s velocity could be calculated by time difference when it passes through the two switches. Because of the weak signal, it is necessary to add an amplifier between the sensor and the PC. In this way, we can make the debris pass through the sensor at a certain path and velocity so that the experiment is more controllable.

4.2. Experimental result

Ferromagnetic debris for the experiment is iron powder which is obtained from a chemical store of China. Since the debris is irregular in shape, Du et al used constructively circle equivalent (CE) diameter to characterize debris size [19]. Since the thickness of the debris may be quite different in this experiment, we use a derivative method (sphere equivalent, SE) to replace it.

The drive current was set as 0.5 A direct current and the amplification factor as 36,658. 20 μm × 800 μm × 800 μm ferromagnetic debris (SE diameter 290 μm), which was fixed by a wax cylinder, moved along the pipe center axis at 0.2 m s⁻¹ speed three times. The direction the second time is opposite to those for the other two. The sensor output signal after amplification is shown in figure 13.

It is observed that there are three similar wave profiles, with the first part having some bigger pulses, the second part like a sine wave and the third part having some smaller pulses. After many experiments, we discovered that the second part is from debris, while the first and third parts are triggered by the vibration when the wax cylinder moves in and out of the sensor.

In order to reduce the interference by vibration and noise, a Chebyshev filter is used to filter the digital signal. The result after the Chebyshev filter is shown in figure 14. After filtering, the three wave profiles can be distinguished as a principal wave and several noise waves. In each wave profile, the first and third parts are obviously weakened, and the second wave is close to a standard sine wave. The waveform similarity of the three waves indicates the superiority of this experimental rig.

A 100 ms segment wave is extracted from figure 14 to simulate the detection accuracy shown in figure 15. It is observed that the curves under test and simulation are basically of the same shape, and their amplitudes are quite close. This result indicates that the sensor model is valid.

4.3. Experimental result analysis

The traditional detection sensitivity evaluation method of the inductive debris sensor focuses on the detected debris size,
Table 1. Sensor sensitivity comparison.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>ODM</th>
<th>HTDS</th>
<th>RDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside diameter of the pipe</td>
<td>12.7 mm</td>
<td>1.2 mm</td>
<td>20 mm</td>
</tr>
<tr>
<td>Coils or iron core axial length</td>
<td>1.27 mm</td>
<td>0.16 mm</td>
<td>10 mm</td>
</tr>
<tr>
<td>Debris size</td>
<td>125 μm (sphere)</td>
<td>50 μm (cube)</td>
<td>20 μm × 800 μm × 800 μm</td>
</tr>
<tr>
<td>Sensitive zone volume</td>
<td>160.84 mm$^3$</td>
<td>0.18 mm$^3$</td>
<td>3140 mm$^3$</td>
</tr>
<tr>
<td>Debris volume</td>
<td>$1.02 \times 10^{-3}$ mm$^3$</td>
<td>$1.25 \times 10^{-4}$ mm$^3$</td>
<td>$1.28 \times 10^{-2}$ mm$^3$</td>
</tr>
<tr>
<td>Volume ratio</td>
<td>157686</td>
<td>1440</td>
<td>245312</td>
</tr>
</tbody>
</table>

Figure 15. Test wave and simulation wave.

Figure 16. Sensor output signal under 100 μm cube ferromagnetic debris.

which is unreasonable to some extent. One reason is that the sensor size is also an important factor for detecting the size. For example, if a sensor is made smaller in equal proportion, then it is obvious that the sensor can detect smaller debris, but it is hard to say that its sensitivity is improved. Another reason is that different shapes of debris cannot be compared by one-dimensional size. Thus, the effective evaluation method should consider sensitive section and debris volume, and we propose the ratio of the sensitive zone volume to debris volume as the sensitivity index. Table 1 shows the sensitivity comparison between the axial inductive debris sensor and the radial inductive debris sensor. It indicates that the volume ratio of RDS is bigger than others, which means that the sensitivity of the inductive debris sensor based on the radial magnetic field (RDS) is better.

4.4. Contrast experiment

Because ODM’s relative sensitivity is better than that of HTDS, this paper designs the contrast experiment for ODM and RDS. Considering that the difference of pipe diameter may impact the experimental result, we utilized the same pipe diameter (12.7 mm) and the same iron core for ODM and RDS. When 100 μm cube ferromagnetic debris moves along the pipe’s center axis at 0.2 m s$^{-1}$, the sensor output is as shown in figure 16.

A large ripple and a convex peak are present in figure 16. The large ripple is 50 Hz noise caused by the power line. Because its frequency is close to the debris signal, it is hard to filter out. The convex peak means that RDS can detect 100 μm cube ferromagnetic debris (SE diameter 124 μm) when the pipe diameter is 12.7 mm while ODM can detect 125 μm sphere ferromagnetic debris under the same condition [15]. Thus, RDS is more sensitive than ODM with the same pipe diameter.

5. Conclusions

This paper presented a new inductive method based on a radial magnetic field. After establishing the mathematical model of this debris detection sensor, this paper provided the detection theory, signal processing and experimental rig. The experimental results indicate that RDS can effectively detect 20 μm thick ferromagnetic debris (SE diameter 290 μm) when the pipe diameter is 20 mm. It has better detection sensitivity compared with the axial inductive debris sensor. In future research, we will optimize the structure and detection performance both in theory and experiment.

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