بحث تأثير السرعة على دقة الفحص لحساس الحث الكهربائي

وو بو، تشانغ هونج بنغ، سون بو تشينغ و تشين هاي تشيوان
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الخلاصة

بالنسبة إلى حساس الحث الكهربائي، تحدث الحركة النسبية بين ملف ثابت وهدف الفحص المعدي أو الملف الآخر، كما أن حساس الحث الكهربائي عادة يستعمل في قياسة الهدف المعدي بالتحرك والدوران والحركة المتكررة. لكن لم يبحث تأثير سرعة الحركة النسبية على دقة حساس الحث الكهربائي. لذلك يبحث تأثير سرعة الحركة للحبيبات المعديه على دقة حساس الحث الكهربائي لنفيند أداء حساس الحث الكهربائي ورفع حساسية الفحص للحبيبات المعديه وتطبيق حساس الحث الكهربائي في المجالات الأخرى. تبحث هذه الرسالة العلاقات بين سرعة حركة الحبيبات المعديه ودقة حساس الحث الكهربائي عبر التحليل النظري والتدقيق التجريبي. تمثل نتيجة التحليل في أنه يمكن رفع دقة الفحص للحساس عبر تخفيف سرعة الحبيبات المعديه. عندما تتخفف سرعة الحبيبات المعديه من 10^{-3}\times 5.8\ m/s إلى 10^{-2}\times 2.9\ m/s، ترفع قيمة الحساس للملف من 0.81\ nH إلى 0.43\ nH وذلك يعني أن دقة الفحص ترفع بـ 87.5%.
Research on the Influence of Velocity on the Sensitivity of Inductive Sensor

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ABSTRACT

In an inductive sensor, relative movement occurs between a fixed coil and a metal target or another coil, and inductive sensors are often used to measure moving, rotating and reciprocating targets. However, the effect of this relative movement on the detection capabilities of inductive sensors has not previously been investigated. Therefore, the influence of velocity on the sensitivity of inductive sensors for metal particle detection should be addressed to improve the performance of inductive sensors in terms of their sensitivity for metal particle detection and in other aspects of their operation. This paper presents a theoretical analysis and experimental validation of the dependence of the sensitivity of an inductive sensor on the velocity of the particles it is measuring. The results indicate that the sensitivity to particles can be significantly improved by decreasing their velocity. When the velocity of the particles is decreased from $2.9 \times 10^{-2} \text{ m/s}$ to $5.8 \times 10^{-3} \text{ m/s}$, the inductance variation of the coil increases from 0.43 nH to 0.81 nH, corresponding to a sensitivity enhancement of 87.5%.

Keywords: Detection sensitivity; inductive sensor; measurement; particle detection; velocity.

INTRODUCTION

Inductive sensors have achieved considerable success because of their low manufacturing cost, high reliability, robustness, resistance to fouling and contact-free operation (Kim 2013; Kejik et al. 2004). The operating conditions of inductive sensors are less strongly affected compared to other types of sensors by environmental factors including humidity, temperature, dust, contamination and mechanical offsets (Bartsch et al. 2012; Rahal et al. 2009; Danisi et al. 2013; Wei et al. 2012). Therefore, they can be applied in certain harsh working environments. Inductive sensors are commonly used in industrial applications, such as in the detection of defects (Cha et al. 2010) or metal wear particles in lubrication oil (Du et al. 2010) or for measurements of temperature (Kim et al. 2000), pressure (Bakhour et al. 2011; Bera et al. 2011), tip clearances (Du et al. 2014), forces (Du et al. 2015), metallic profiles (Passeraub et al. 1998), positions (Zhang et al. 2013; Aschenbrenner et al. 2015) and displacements (Tang et al. 2015; Coskun et al. 2013).

Relative movement typically occurs in an inductive sensor between a fixed coil and a metal target or another coil, and inductive sensors are often used to measure moving, rotating and reciprocating targets. However, the effect of this relative movement (or velocity) on the detection capabilities of inductive sensors has not previously been investigated. Therefore, the influence of velocity on the sensitivity of inductive sensors for metal particle detection should be addressed to improve the performance of inductive sensors in terms of their sensitivity for metal particle detection and in other areas of application.
In previous work, it has been found that identical particles traveling at different velocities
induce different signals in inductive sensors. In other words, the particle velocity can be adjusted
to enhance the sensitivity of an inductive sensor. This paper presents a theoretical analysis and
experimental validation of the effect of particle velocity on the sensitivity of inductive sensors.

**THE PRINCIPLE OF PARTICLE DETECTION**

In the scenario illustrated in Figure 1(a), when an alternating current (AC) voltage is applied
across the planar coil, a magnetic field is induced around the coil, and an induced electromotive
force $\varepsilon$ is generated in accordance with the Faraday’s law of electromagnetic induction. Because
the metal conductor forms a closed loop, eddy currents are generated. According to Lenz’s law, the
direction of the eddy current will oppose the change that produced it, and the electromotive force
$\varepsilon$ induced in the metal conductor can be expressed as

$$\varepsilon = -\frac{d\Phi}{dt}$$  \hspace{1cm} (1)

A diagram of a microfluidic chip based on an inductive sensor is presented in Figure 1(b). When
a high-frequency AC voltage is applied across the coil, eddy currents are generated in a metallic
particle as it passes through the channel, and the magnetic field of these eddy currents, which
opposes the magnetic field of the coil, is detected by the coil, causing a change in the inductance.

![Diagram of a microfluidic chip](image)

**Fig. 1.** Schematic of the microfluidic chip for metal particle detection in oil

**MODEL ESTABLISHMENT**

Based on the detection principle described above, a mathematical model of the electromotive
force $\varepsilon$ induced in the metallic particle can be established as follows. $B$ is the magnetic field
intensity of the coil, and $E_{in}$ is the electric field intensity induced in the particle. According to the
Faraday law of electromagnetic induction, the induced electromotive force $\varepsilon$ can be expressed as

$$\varepsilon = \oint_c E_{in} \cdot dl = -\frac{d\phi}{dt} = -\frac{d}{dt} \int_s B \cdot dS = -\oint_s \left( \frac{\partial B}{\partial t} \cdot dS + B \cdot \frac{\partial}{\partial t} dS \right)$$  \hspace{1cm} (2)
The first term on the right-hand side is the magnetic field with respect to time, $\varepsilon_t$, and the second term on the right-hand side is the closed-loop eddy current with respect to time, $\varepsilon_m$. Thus, the induced electromotive force $\varepsilon$ can be divided into the following components:

$$
\varepsilon_t = -\frac{d\phi_t}{dt} = -\oint_S \frac{\partial B}{\partial t} \cdot dS
$$

(3)

$$
\varepsilon_m = -\frac{d\phi_m}{dt} = -\oint_S B \cdot \frac{\partial}{\partial t} dS
$$

(4)

The movement of the closed loop forming the eddy current is illustrated in Figure 2.

![Fig. 2. Movement of the closed loop inside the particle](image)

It is assumed that the closed loop $C$ moves from $C(t)$ to $C(t+dt)$ at velocity $v$ in $dt$. There are two different areas surrounded by $C(t)$: $S_1$ and $S_2 + S_3$. Thus, $d\phi_m$ in Equation (4) can be expressed as

$$
d\phi_m = \phi_{S_2} - \phi_{S_1} = \phi_{S_2} - (\phi_{S_2} + \phi_{S_3}) = -\phi_{S_3}
$$

(5)

As seen from Figure 2, the effect of this movement on the magnetic flux can be expressed as

$$
d\phi_m = -\phi_{S_3} = -\oint_C B \cdot (dl \times v) dt
$$

(6)

The effect of the movement on the induced electromotive force $\varepsilon_m$ can then be expressed as

$$
\varepsilon_m = -\frac{d\phi_m}{dt} = \oint_C B \cdot (dl \times v) = \oint_C (v \times B) \cdot dl
$$

(7)

According to the Stokes formula and Equation (7), Equation (2) can be expressed as:

$$
\nabla \times \mathbf{E}_{in} = -\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (v \times \mathbf{B})
$$

(8)
It is assumed that the particle is moving in the x direction and that the magnetic field of the coil is uniformly distributed. $B_i$ is the magnetic field intensity of the coil due to the movement of the particle, and $E_i$ is the induced electric field intensity due to the movement of the particle; thus, Equation (9) can be obtained as follows:

$$\mathbf{B}_1(x, t) = \mathbf{B}(x - vt, t)$$

From this equation, Equation (10) can be obtained:

$$- \frac{\partial \mathbf{B}_1}{\partial t} = - \frac{\partial \mathbf{B}}{\partial t} + v \frac{\partial \mathbf{B}}{\partial x}$$

In Equation (10), $v(\partial \mathbf{B}/\partial x)$ can be expressed as $(\mathbf{v} \cdot \nabla) \mathbf{B}$.

The equation for the transformation of the operator $\nabla$ can be expressed as

$$\nabla \times \mathbf{B} \times \mathbf{v} = (\mathbf{v} \cdot \nabla) \mathbf{B} + \nabla \times \mathbf{B} - \mathbf{B} \cdot \nabla \mathbf{v} - (\nabla \cdot \mathbf{B}) \mathbf{v}$$

$$\nabla \cdot \mathbf{B} = 0$$

can be obtained according to the Maxwell equations, and the velocity $\mathbf{v}$ is a constant vector; thus, Equation (11) can be expressed as

$$\nabla \times \mathbf{B} \times \mathbf{v} = (\mathbf{v} \cdot \nabla) \mathbf{B}$$

Using Equation (12), Equation (10) can be expressed as

$$- \frac{\partial \mathbf{B}_1}{\partial t} = - \frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{B} \times \mathbf{v})$$

According to the differential form of the Maxwell equations,

$$\nabla \times \mathbf{E}_1 = - \frac{\partial \mathbf{B}_1}{\partial t}$$

$$\nabla \times \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t}$$

Thus, Equation (13) can be expressed as

$$\nabla \times \mathbf{E}_1 = \nabla \times \mathbf{E} + \nabla \times (\mathbf{B} \times \mathbf{v})$$

The electric field intensity due to the movement of the particle can then be expressed as

$$\mathbf{E}_1 = \mathbf{E} + \mathbf{v} \times \mathbf{B}$$

Equation (17) indicates that the electromotive force $\mathcal{E} = \int_C \mathbf{E} \cdot d\mathbf{l}$ induced in the particle will increase as the velocity of the particle increases.

In addition, the inductance variation of coil is supposed to be expressed as below:

$$\Delta Z_{\text{coil}} = Z - Z_0 = jw \sum_{i=1}^{N} \int_S \Delta B dS$$

$$\Delta L_{\text{coil}} = \frac{\text{imag}(\Delta Z_{\text{coil}})}{w}$$
According to Lenz’s law, the direction of the induced electromotive force $\varepsilon$ is opposite to that of the magnetic field of the coil. As a result, the inductance of the coil decreases with an increasing particle velocity.

The distribution of the magnetic flux density is evaluated by Comsol software based on the mathematical model, as discussed above. For instance, the magnetic flux density in the velocity of particle $5.8 \times 10^{-3}$ m/s is shown in Figure 3, the value of the magnetic field far away from the iron particle surface is 0.018 T in average, and the value at the surface of the particle is 0.04 T, and the value is increasing up to 0.05 T inside the particle, while the magnetic field is decreasing down to 0.001 T in the core region because of the skin effect of the high frequency magnetic field. According to Equation (18) and Equation (19), the inductance variation of coil are calculated with different magnetic flux density $B$ and velocity of particles, as shown in Table 1.

![Figure 3. The distribution of magnetic flux density (vparticle= 5.8×10⁻³ m/s)](image)

<table>
<thead>
<tr>
<th>Velocity of particles (m/s)</th>
<th>5.8×10⁻³</th>
<th>1.16×10⁻²</th>
<th>1.74×10⁻²</th>
<th>2.32×10⁻²</th>
<th>2.9×10⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance variation of coil (nH)</td>
<td>0.85</td>
<td>0.75</td>
<td>0.66</td>
<td>0.53</td>
<td>0.46</td>
</tr>
</tbody>
</table>

**EXPERIMENTAL VALIDATION**

First, a mold for a chip with a microfluidic channel was fabricated using copper wire with a diameter of 270 μm, and a one-layer planar coil was fabricated with 33 turns of copper wire with a diameter of 50 μm. Second, casting material for the chip was fully mixed at a 10:1 ratio of liquid polydimethylsiloxane (PDMS) and curing agent. Then, the mold was filled with the liquid PDMS and placed in an incubator with a thermostat. The incubator was heated to 60°C and maintained at
this temperature for two hours. Third, the solid PDMS was trimmed, and the mold of the fluidic channel was removed. Finally, a glass substrate was installed after the plasma cleaning of the bottom of the chip and the surface of the glass slide. A photograph of the final microfluidic chip is shown in Figure 4.

As shown in Figure 5, the experimental system consisted of a syringe pump (Harvard Apparatus, 70-2212), the fabricated microfluidic chip, an inductance-capacitance-resistance (LCR) meter (Agilent E4980A, Santa Clara, CA) and a computer. LabVIEW® was used to stabilize the measured inductance signals. A 2 V, 2 MHz AC voltage was supplied by the LCR meter. For each test, a mass of 10 mg of particles was weighed using a precision balance (XS225A, precision: 0.1 mg) and then mixed with 50 mL of Hyspin AWS 10 hydraulic oil. Iron particles (Shahong Electromechanical Technology Company, Hefei, China) with a diameter of 80 μm are applied for the test.

The movement of the particles was controlled by the syringe pump, and the volume flows of the syringe pump were set to 0.02 mL/min, 0.04 mL/min, 0.06 mL/min, 0.08 mL/min and 0.10 mL/min, corresponding to particle velocities of $5.8 \times 10^{-3}$ m/s, $1.16 \times 10^{-2}$ m/s, $1.74 \times 10^{-2}$ m/s, $2.32 \times 10^{-2}$ m/s and $2.9 \times 10^{-2}$ m/s, respectively.

In the experiments, 4 groups of tests were recorded at each velocity. The other parameters - i.e., temperature, particle size, voltage of the excited signal, frequency of the excited signal, etc. - were held constant.

The numerical experimental data and the trace of the inductive pulses in the coil at a particle velocity of $5.8 \times 10^{-3}$ m/s are shown in Table 2 and Figure 6, respectively. According to Table 2, the
average inductance variation of the coil was 0.81 nH at a particle velocity of $5.8 \times 10^{-3}$ m/s. Similar inductive pulses in the coil recorded at particle velocities of $1.16 \times 10^{-2}$ m/s, $1.74 \times 10^{-2}$ m/s, $2.32 \times 10^{-2}$ m/s and $2.9 \times 10^{-2}$ m/s are shown in Figure 7.

**Table 2.** Experimental data recorded at a particle velocity of $5.8 \times 10^{-3}$ m/s

<table>
<thead>
<tr>
<th>Test number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base inductance of coil (μH)</td>
<td>4.29357</td>
<td>4.29357</td>
<td>4.29357</td>
<td>4.29357</td>
</tr>
<tr>
<td>Maximum inductance of coil (μH)</td>
<td>4.29439</td>
<td>4.29436</td>
<td>4.29439</td>
<td>4.29438</td>
</tr>
<tr>
<td>Inductance variation of coil (nH)</td>
<td>0.81786</td>
<td>0.78786</td>
<td>0.81786</td>
<td>0.80786</td>
</tr>
<tr>
<td>Average inductance variation of coil (nH)</td>
<td>0.807857</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation of inductance variation (nH)</td>
<td>0.001414214</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 6.** Inductive pulses in the coil at a particle velocity of $5.8 \times 10^{-3}$ m/s in test 1

**Fig. 7.** Inductive pulses in the coil recorded at various particle velocities
The numerical experimental data recorded at all different particle velocities are summarized in Table 3. In this table, the rates of inductance variation of the coil for the different velocities are calculated with respect to the average inductance variation of the coil at a particle velocity of \(2.9 \times 10^{-2}\) m/s, which is treated as the reference.

**Table 3. Summary of the experimental data**

<table>
<thead>
<tr>
<th>Volume flow (mL/min)</th>
<th>0.02</th>
<th>0.04</th>
<th>0.06</th>
<th>0.08</th>
<th>0.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity of particles (m/s)</td>
<td>(5.8 \times 10^{-3})</td>
<td>(1.16 \times 10^{-2})</td>
<td>(1.74 \times 10^{-2})</td>
<td>(2.32 \times 10^{-2})</td>
<td>(2.9 \times 10^{-2})</td>
</tr>
<tr>
<td>Inductance variation of coil (nH)</td>
<td>0.807857</td>
<td>0.700833</td>
<td>0.6098</td>
<td>0.507885</td>
<td>0.430789</td>
</tr>
<tr>
<td>Rate of inductance variation of coil</td>
<td>87.52945%</td>
<td>62.68581%</td>
<td>41.55406%</td>
<td>17.89625%</td>
<td>0%</td>
</tr>
<tr>
<td>Standard deviation of inductance variation (nH)</td>
<td>0.00141421</td>
<td>0.00129099</td>
<td>0.00129099</td>
<td>0.00478714</td>
<td>0.00404145</td>
</tr>
</tbody>
</table>

As shown in Table 3, when the velocity of the particles was decreased from \(2.9 \times 10^{-2}\) m/s to \(5.8 \times 10^{-3}\) m/s, the magnitude of the inductance variation of the coil increased from 0.43 nH to 0.81 nH, corresponding to a sensitivity enhancement of 87.5\%, and the standard deviation of the inductance variation decreased from 0.00404145 nH to 0.00141421 nH.

According to Table 1 and Table 3, the inductance variations including the experimental and simulation data, which are affected by the velocity of particles, are shown in Figure 8. The relationship between the rate of the inductance variations of coil and the velocity of particles is shown in Figure 9.

![Fig. 8. Inductance variations affected by the velocity of particles](image-url)
As shown in Figure 8, the differences of two data are between 4.6% and 8.9%, which is validated by comparing the experimental data with theory model. It is concluded that the inductance variation of coil increases and the standard deviation decreases as the velocity of particles decreases.

![Graph showing the relationship between the rate of inductance variation of coil and the velocity of particles.](image)

**Fig. 9.** Relationship between the rate of inductance variations of coil and the velocity of particles

According to the Figure 9, it is concluded that the rate of inductance variation decreases as the velocity of particles increases, and the relationship between them is an approximation of a linear dependency.

From the discussion above, it is recognized that the experiment results agreed with the theoretical analysis, and the sensitivity can be improved by decreasing the velocity of particles.

**CONCLUSION**

This paper presents research conducted to investigate the effect of the relative particle velocity on the signal pulses observed in inductive sensors. This work is expected to enable the improvement of inductive sensors in terms of their sensitivity for metal particle detection and in other aspects of their performance. A theoretical analysis and experiment validation are reported. Iron particle velocities of $5.8 \times 10^{-3}$ m/s, $1.16 \times 10^{-2}$ m/s, $1.74 \times 10^{-2}$ m/s, $2.32 \times 10^{-2}$ m/s and $2.9 \times 10^{-2}$ m/s were investigated in the experiment. When the velocity of the particles was decreased from $2.9 \times 10^{-2}$ m/s to $5.8 \times 10^{-3}$ m/s, the inductance variation of coil increases from 0.43 nH to 0.81 nH, corresponding to a sensitivity enhancement of 87.5%, and the standard deviation of the inductance variation decreased from 0.00404 nH to 0.00141 nH. These results indicate that the sensitivity can be significantly improved by decreasing the velocity of particles, which is expecting to provide the guideline to improve the performance of the inductive sensor on metal particle detection and other application area.
REFERENCES


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