Specific Cylindrical Metal’s Distinction In Particular Environment

YANJIE WANG, QING LI, XIONG LI
College of Electrical and Mechanical Engineering
China Jiliang University
China Jiliang University, Hangzhou, 310018
CHINA
E-mail: wangyanjiexx@163.com

Abstract: - To solve the problem about specific cylindrical metal’s distinction in particular environment, in this paper we have designed a new eddy current sensor. And, the orthogonal vector LIA( Lock-in Amplifier) was applied to realize getting useful signals of the new sensor. After the calculation of DSP, we can get the planar information about phase and amplitude of the getting useful signal. The small differences of the copper cylinder can be easily distinguished.

Keywords: - Specific cylindrical metal, A new eddy current sensor, Orthogonal vector LIA

1 Introduction

In certain occasions we need distinguish specific cylindrical metal in particular environment, this is very important to some body in some times.

The testing environment discussed in this paper as shown in figure 1, the tested copper cylinder completely surrounded by the copper around it. The testing space is only one long and narrow crack, the length, the width and the height of which is respectively 4cm, 0.08cm and 0.16cm. The purpose of testing is to distinguish the differences of some copper cylinders whose necks are different but their height (8mm) and diameter (3mm) are the same within the above environment for some special needs.

Fig.1. The particular environment

2 THEORY OF TESTING

When a conductor is exposed to a changing magnetic field, these will be a circulating flow of electrons, or a current within the body of the conductor. These circulating eddies of current create induced magnetic fields that oppose the change of the original magnetic field due to Lenz's law, causing repulsive or drag forces between the conductor and the magnet. This phenomenon is called the eddy current effect.

According to the eddy current effect of the above, some of the non-electrically changes can be converted into the changes of impedance (or the changes of inductance, the changes of quality factor), thus some non-electrically changes can be measured by this way.

Fig.2. The eddy current effect

As shown in Figure 2, a circular coil carrying an
AC current $I_1$ is placed in close proximity to an electrically conductive specimen (specific cylindrical metal). The alternating current in the exciting coil generates a changing magnetic field (H1), which interacts with the tested object and induces eddy currents ($I_2$) within the body of the conductor. These swirling currents dissipate energy, and create a magnetic field (H2) that tends to oppose to the original field (H1) and this will cause some changes in the characteristics of the exciting coil, for example, the changes of impedance, the changes of inductance and the changes of the quality factor[1].

In general, the impedance, the inductance and the quality factor of the exciting coil will different with the differences of the geometric shapes, the conductivity, the permeability of the tested conductor[2]. If just one parameter of the above parameters change and the rest are constant, it can be taken as a sensor on the changing parameter.

According to the eddy current effect and the specific testing environment of the above, In this paper, the testing method is designed as shown in figure 3, the exciting coil generates a changing magnetic field, when the tested cylindrical metal is placed in the hole of the exciting coil, there will a induced current generated in the cylindrical metal, Magnetic field generated by the eddy current will affect the magnetic field generated by the exciting coil and then affect the parameters of the equivalent circuit of the exciting coil as shown in figure 4. For example, the inductor value will decrease as the result of the opposite magnetic field and the impedance will increase as the result of the energy that the swirling currents dissipate.

![Fig.3. The testing method based on the eddy current](image)

According to circuit theory, Figure 3 can be simplified to such a circuit model as shown in figure 4. Assumed that the original resistance of the exciting coil is $R_1$, the original inductance $L_1$, and the impedance is 

$$Z_1 = R_1 + j\omega L_1$$

When the tested copper cylinder is placed in the hole of the exciting coil, it can be see as a coupled inductor. Then it can be considered that there is a mutual inductance between the coil and the conductor and the mutual inductance will decrease as the neck of the tested copper cylinder increase. The swirling current within the tested copper cylinder can be seen as a turn of short-circuit coil of which the resistance is $R_2$ and the inductance is $L_2$.

![Fig.4. The equivalent circuit of figure 3](image)

The equivalent circuit shown in figure 4 can be described by the following circuit equations due to Kirchhoff's law:

$$\begin{align*}
R_1 I_1 + j\omega L_1 I_1 - j\omega M I_2 &= U \\
R_2 I_2 + j\omega L_2 I_2 - j\omega M I_1 &= 0
\end{align*}$$

Then

$$\begin{align*}
I_1 &= \frac{U}{R_1 + \frac{\omega^2 M^2}{R_2^2 + (\omega L_2)^2}} + \frac{\omega L_1 - \frac{\omega^2 M^2}{R_2^2 + (\omega L_2)^2}}{R_2^2 + (\omega L_2)^2} I_2 \\
I_2 &= \frac{\omega M L_2 + j\omega M R_2}{R_2^2 + (\omega L_2)^2} I_2
\end{align*}$$

Where, $R_1$ and $L_1$ are the resistance and the inductance of the exciting coil; $R_1$ and $L_2$ are the resistance and the inductance of the tested copper.
cylinder; $U$ is the exciting voltage. From equation

$$I_1$$ we can see that after the tested copper cylinder is placed in the hole of the primary exciting coil, the impedance of which become

$$Z = \left( R_1 + R_2 \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2} \right) + j \omega \left( L_1 - L_2 \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2} \right).$$

The equivalent resistance is

$$R = R_1 + R_2 \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2}.$$  

(5)

The equivalent inductance is

$$L = L_1 - L_2 \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2}.$$  

(6)

The quality factor is

$$Q = \frac{\omega L_1}{R_1} \frac{1 - \frac{L_2}{L_1} \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2}}{1 + \frac{R_2}{R_1} \frac{\omega^2 M^2}{R_2^2 + \omega^2 L_2^2}}.$$  

(7)

In equation 5, the equivalent resistance $R$ is always large than the primary resistance $R_1$ due to energy that the swirling current dissipate. The first part of the equation 6 $L_1$ is the inductance of the exciting coil, the second associated with the eddy current effect. Anti-magnetic field caused by eddy current reduce the inductance of the exciting coil and the shorter the copper cylinder’s neck is, the more the inductance drop.

According to equation 7, the quality factor $Q$ of the exciting coil is

$$Q = Q_1 \frac{1 - \frac{L_2}{L_1} \frac{\omega^2 M^2}{Z_2^2}}{1 + \frac{R_2}{R_1} \frac{\omega^2 M^2}{Z_2^2}}.$$  

(8)

In the equation 8, $Q_1$ is the primary quality factor of the exciting coil, $Z_2$ is the equivalent impedance of the swirling current within the body of the tested copper cylinder,

$$Z_2 = \sqrt{R_2^2 + (\omega L_2)^2}.$$

We can see from the above that the impedance, the inductance and the quality factor of the exciting coil will all different with the differences of the tested copper cylinder’s necks. Therefore, the eddy current sensor circuit can use one or more parameters of $Z$, $L$ and $Q$, and converts them into electricity, which can achieve the purpose of measuring.

3 The design of eddy current sensor

In order to achieve the measuring method as shown in figure 3, we’ve designed a sensor structure as shown in figure 5 so that we can easily insert the sensor into the actual measured mechanism in the course of using. Beside that we have found in the experiment that the sensor coil covered with a thin iron hoop has better sensitivity and resolution, at the same time the hoop can reduce the impact caused by the around metal and the external electromagnetic fields[3]. Therefore, the thin iron hoop can improve the performances of the sensor.

Fig.5. The structure of the eddy current new sensor

Fig.6. The exciting coil with a iron hoop

The testing effect of the new designed sensor is shown in table 1.
Table 1. The testing performance of the new designed sensor

<table>
<thead>
<tr>
<th>No Copper Cylinder</th>
<th>Resistance of the Sensor (uH)</th>
<th>Inductance of the Sensor (Ω)</th>
<th>Quality Factor of the Sensor (μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24.9587</td>
<td>3.78417</td>
<td>414.101</td>
</tr>
<tr>
<td>Insert the Copper Cylinder 2</td>
<td>24.9409</td>
<td>3.81945</td>
<td>410.579</td>
</tr>
<tr>
<td>Insert the Copper Cylinder 2</td>
<td>24.9076</td>
<td>3.82057</td>
<td>409.907</td>
</tr>
<tr>
<td>Insert the Copper Cylinder 3</td>
<td>24.9201</td>
<td>3.82456</td>
<td>409.468</td>
</tr>
</tbody>
</table>

The length of necks of the three copper cylinders in Table 1 are respectively 1.53mm, 0.91mm, 0.47mm and the test apparatus is Agilent 4294.

Fig. 7. The hardware block diagram of the signal processing circuit

4 Sensor output signal processing and the Copper Cylinder’s distinction

Due to the skin effect, axial distribution of the eddy current density within the body of the copper cylinder become weak in the exponential law with the increase of the depth. If we test the copper cylinder like the way shown in figure 3, the change of the impedance of the coil which is caused by the difference of the length of the upper neck of the copper cylinder is very small. To measure such a weak signal, we usually use lock-in amplifier, but the output of normal lock-in amplifier is the cosine value of the phase, so that the testing ability is not strong enough. In this article, we use the orthogonal vector lock-in amplifier[4], and the output is the tangent value of the phase. It has higher sensitivity to detect weak signal. The hardware block diagram of the signal processing circuit is shown in figure 7.
Fig. 8. The testing bridge

The testing bridge is shown in figure 8. L1 and L2 are the sensors said in III. R1 and R2 are two precision resistances. In order to simplify the analysis process, we suppose that the output voltage of the two-leg of the bridge are

\[
\begin{align*}
U_1 &= E_1 \sin(2\pi ft + \phi_1) \\
U_2 &= E_2 \sin(2\pi ft + \phi_2)
\end{align*}
\] (9)

Then we multiply U1 and U2 and the output is

\[
U_o' = U_1^2 = \frac{E_1E_2}{2} \cos(\phi_1 - \phi_2) + \frac{E_1E_2}{2} \cos(4\pi ft + (\phi_1 + \phi_2))
\]

---------- (10)

Then U2 is delayed by 90 °and become

\[
U_2' = E_2 \sin(2\pi ft + \phi_2 - 90°) = -E_2 \cos(2\pi ft + \phi_2)
\]

---------- (11)

Then we multiply U_2' and U_1 and the output is

\[
U_o'' = U_1U_2' = \frac{E_1E_2}{2} \sin(\phi_1 - \phi_2) - \frac{E_1E_2}{2} \sin(4\pi ft + (\phi_1 + \phi_2))
\]

---------- (12)

The formula (10) and the formula (12) show that the output of the multiplier is composed of two parts, the first one is difference-frequency component and the second one is sum-frequency component. The spectrum changes from one spectrum whose center frequency is f into two spectrums whose center frequencies are respectively 0 and 2f after the process of the multiplier. And these changes of the spectrum make we conveniently to use the low-pass filter.

We can get rid of the frequency-doubled component of the output of the multiplier by a low-pass filter and the Uo1 and Uo2 become:

\[
\begin{align*}
U_{o1}' &= \frac{E_1E_2}{2} \cos(\phi_1 - \phi_2) \\
U_{o2}' &= -\frac{E_1E_2}{2} \sin(\phi_1 - \phi_2)
\end{align*}
\] (13)

Then use U_{o2}' divided by U_{o1}' to get the tangent-type output Uo.

\[
U_o = \frac{-\frac{E_1E_2}{2} \sin(\phi_1 - \phi_2)}{\frac{E_1E_2}{2} \cos(\phi_1 - \phi_2)} = -\tan(\phi_1 - \phi_2)
\]

(14)

Then put U_o through the inverting scaling circuit and get

\[
\begin{align*}
U_o' &= \tan(\phi_1 - \phi_2)
\end{align*}
\]

Then put U_o, U_o', and U_o'' into the three channels of high-precision A/D. After the calculation of DSP we can get the phase (\phi_1 - \phi_2) and the product of the two amplitude E_1 \cdot E_2 of the bridge’s output signal. We can distinguish the differences of the copper cylinders according to the differences of the two-dimensional information about phase and amplitude of the bridge’s output signal which are caused by putting the copper cylinder into one coil of the bridge.

5 CONCLUSION

To solve the problem about specific cylindrical metal’s distinction in particular environment, in this paper we have designed a new eddy current sensor according to the principle of electromagnetic induction. Although the output signal of the sensor coil is very weak, after the amplification of the orthogonal vector lock-in amplifier and the calculation of DSP we have been able to detect the differences of the three copper cylinders in table 1. Although we have achieved some success on specific cylindrical metal’s distinction in particular environment, there are also some defects in our work, for example the anti-interference ability of our circuit is not very good enough. We still have a lot of work to do on specific cylindrical metal’s distinction in particular environment.
References: