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Inductive sensor to detect metal impurities in non-metallic medium

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Abstract. The mathematical model for an induction detector intended for detection of metal impurities is examined. The detector consists of three coils. The centre coil serves to induct a magnetic moment in the metal sample, and side coils are used to record this moment during the sample propulsion through the detector. It is shown that at an identical value of the magnetic field induction, created by the induction coil in the unit volume of the sample, the induced magnetic moment is defined by magnetic susceptibility for ferromagnetics, and for nonmagnetic materials – by their electric conductivity.

1. Introduction
In the manufacture of linoleum, lace tablecloths, sticky tapes, adhesive tape, etc., the plasticized mass, consisting of polyvinyl chloride resins, chalk and plasticizers are used. After several preparatory operations, this mass is fed to a 4-roll calender. The practice shows that due to the original substances, a hit of metallic impurities in the plasticized mass takes place [1-10]. This leads, on the one hand, to the reduction of the grade of quality of the finished product, and, on the other hand, – to the damage of calender rolls.

2. The mathematical model
A model of the induction sensor consisting of three coaxial coils to detect metallic impurities was examined. The center (generator) coil is used for the magnetic moment guidance in a metal sample. To do this, the alternating current from an audio generator is conducted through it. Side (receiving) coils are used to register the magnetic moment induced in the metal sample during its movement through the sensor. The interaction of metal particles possessing a magnetic moment with a receiving coil of the sensor is shown in figure 1.

The magnetic flux generated by a metal particle during its movement through the sensor can be determined. It is known [1] that the vector potential of the magnetic field generated by a moving particle is determined by the following formula:

\[ \vec{\mathcal{A}} = \frac{[\vec{M} \cdot \vec{R}]}{R^5}, \]  

where \( \vec{R} \) is the radius – vector from the particle to the point of the magnetic field.
The vector of the magnetic field, generated by a moving particle at the point determined by the radius-vector, is calculated as follows:

\[ \mathbf{B} = \text{rot} \mathbf{A} . \]  

(2)

Magnetic flux \( F \), which occurs in the plane of the receiving coil due to the movement of magnetized particles can be determined as follows:

\[ F = \frac{\int_B dS = \int S \text{rot} \mathbf{A} dS}{} . \]

(3)

where, \( S \) is the area of the spool.

Transforming equation (3) in accordance with the Stokes theorem, we get:

\[ F = \frac{\int_A d\mathbf{S} = \frac{\int M \cdot \mathbf{R}}{R^3} d\mathbf{R} }{} . \]

(4)

Transiting into cylindrical coordinates, we get:

\[ F = \frac{\int \mathbf{M} \cdot \mathbf{\hat{e}}_\phi \cdot d^2 \cdot \mathbf{\hat{e}}_\phi \cdot \frac{1}{4} \left( \frac{d^2}{4} + z^2 \right)^{3/2} d\phi}{} , \]

(5)

where \( \mathbf{\hat{e}}_\phi \) is a single vector; \( d \) – the diameter of a coil turn; \( z \) – the particle coordinate.

After the integration, considering the number of turns \( n \) in the receiving coil, equation (5) transforms into:

\[ F = \frac{\pi d^2}{2} \cdot \frac{M \cdot n}{\left( \frac{d^2}{4} + z^2 \right)^{3/2}} . \]

(6)
As we previously noted, the sensor consists of three coils – two identical receiver coils and one generator coil. The generator coil is located between receiver coils. This sensor design allows obtaining the same electromotive force (EMF) for receiver coils by letting the alternating current through the generator coil. During the opposite connection of the receiver coils, the resulting EMF, induced in them by the generator coil, will be equal to zero. The scheme of the receiving coil position in the sensor is shown in figure 2.

The magnetic flux generated in these coils by a metal particle moving through the sensor, considering its oncoming inclusion, will be determined by the expression:

\[
F = \frac{\pi d^2}{2} \cdot n \cdot M \cdot \left[ \frac{1}{\left( \frac{d^2}{4} + \left( z - \frac{l}{2} \right)^2 \right)^{3/2}} - \frac{1}{\left( \frac{d^2}{4} + \left( z + \frac{l}{2} \right)^2 \right)^{3/2}} \right].
\]  

(7)

Induction EMF \( e \) induced by this flow in the receiver coils of the sensor is equal to:

\[
e = -\frac{1}{c} \frac{dF}{dt} \approx -\frac{j \omega}{c} F,
\]

(8)

where, \( c \) is the speed of light; \( \omega \) is the cyclic frequency of the current in the generator coil of the sensor.

From equations (7) and (8), it is seen that the EMF generated in the receiving coils varies with the frequency which is equal to the frequency of the current oscillations in the generator coil of the sensor. In this case, the envelope of the peak values for EMF of reception coils during the movement of metallic particles through the sensor is shown in figure 3.

The magnetic moment induced on the metal particle by the magnetic field generated by the generator coil depends on the magnetic properties of this particle.

For ferromagnetic particles, the induced magnetic moment has two components. The first component is determined by the vector of magnetization of the substance, and the second – by induction currents generated in the sample by the alternating magnetic field. It is known [1] that for ferromagnetic materials the first component is bigger than the second one.
Therefore, with a high degree of accuracy, it can be assumed that the magnetic moment for a ferromagnet is determined by expression

\[ M_z = \chi \cdot B_g \cdot V, \]  

(9)

where \( \chi \) is the magnetic susceptibility; \( B_g \) – the induction magnetic field generated by the generator coil sensor; \( V \) – the volume of the particle.

The analysis of equations (7)-(9) shows that in the case of the ferromagnetic material generated in the receiving coils, EMF depends mainly on the frequency of current \( \omega \) of the generator coil and particle volume \( V \). The dependence of the EMF on speed of the particle movement through the sensor is substantially less than the frequency of the current in the generator coil. Indeed, with the oscillator frequency of 4 kHz, \( \omega = 2.5 \cdot 10^4 \) 1/s and speed \( v \) of a particle passing through the sensor makes an input of order \( \frac{dZ}{dt} \approx \frac{v}{d} = \frac{2 \cdot 10^2}{8} = 25 \) 1/s.

If the metal has paramagnetic or diamagnetic properties (\( \mu = 1, \chi = 0 \)), the magnetization vector is equal to zero. Consequently, the magnetic moment of this sample is created only by induction currents induced therein by the magnetic field of the generating coil.

According to Maxwell’s equation [2], the electric field strength can be recorded as follows:

\[ \text{rot}E = -\frac{1}{c} \frac{dB}{dt} = -\frac{j \omega}{c} \cdot B_g. \]  

(10)

After transiting to cylindrical coordinates, we will obtain:

\[ 2\pi \cdot r \cdot E_\varphi = -\frac{j \omega}{c} \cdot B_g \cdot \pi \cdot r^2, \]  

(11)

where \( r \) is the current radius of cylindrical particles.

Consequently, the electric field created by the generator coil of the sensor can be expressed by equation

\[ E_\varphi = -\frac{j \omega \cdot r}{2c} \cdot B_g. \]  

(12)

The density of the induced current in a metallic sample according to Ohm’s law will be equal to

\[ i_\varphi = \sigma \cdot E_\varphi = -\frac{j \omega \cdot r}{2c} \cdot \sigma \cdot B_g, \]  

(13)

where \( \sigma \) is the conductivity of the particle.

The magnetic moment generated in a metal sample by inductive currents can be determined by equation
\[ \vec{M} = \frac{1}{2c} \int \left[ \vec{r} \cdot \vec{i} \right] dV. \] (14)

Following the scheme of particle movement through the sensor (figure 1), it is shown that the magnetic moment of the particle is directed along the Z-axis, therefore

\[ M_z = \frac{1}{2c} \int \vec{r} \cdot \vec{i}_\phi \cdot dV. \] (15)

The equation (13) allows one to obtain

\[ M_z = -\frac{j \omega \cdot \sigma}{4c^2} \cdot B_g \int r^2 \cdot dV. \] (16)

After integration of equation (16), we have:

\[ M_z = -\frac{j \omega \cdot 2\pi \cdot \sigma \cdot B_g \cdot a^5}{15c^2}. \] (17)

where \( a \) – the characteristic size of the particle.

Regarding the metal particle as spherical, we will obtain:

\[ M_z = -\frac{j \omega \cdot \sigma \cdot B_g}{12.11 \cdot \pi^{2/3} \cdot c^2} \cdot \nu^{5/3}. \] (18)

3. Conclusion

Examining equations (9) and (18), we can conclude the following. At the same value of the magnetic field generated by the generator coil in a single volume of the sample, the induced magnetic moment for ferromagnetic material is determined by the magnetic susceptibility, and paramagnetic and diamagnetic materials depend on the material conductivity. Therefore, for ferromagnetic materials, \( M_z \approx \chi \), i.e. it is much greater than one; for para- of diamagnetic materials (\( \omega = 4kHz \), \( M_z \approx 0.1 \)) for copper samples, induced magnetic moments are equal to almost one.

In the case of non-magnetic materials, the induced magnetic moment (see 18) is determined by the particle conductivity and by its volume. Thus, it is evident that the particle volume effect for non-magnetic materials is much greater than that for ferromagnets.

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