The investigation of magnetization reversal loss sensor

R G Vildanov, A S Khismatullin and N N Luneva
Branch of Ufa State Petroleum Technological University in Salavat, 22B, Gubkina Str., Republic of Bashkortostan, Salavat 453250, Russian Federation

E-mail: him5az@mail.ru

Abstract. A sensor was developed to measure the losses in the magnetization reversal of materials. Expressions for the magnetic flux in the sensor core and the sensitivity for the amplitude processing of the signal from the magnetization reversal losses are obtained. A vector diagram of the currents and voltages is plotted, along which the phase shift of the signal from the magnetization reversal losses is determined. It is established that the phase shift of the current is due to two factors. The formula of the total phase shift from both factors is obtained. The total phase shift is directly proportional to the induction in the product and the mass of the magnetized zone, and hence the volume of the defects. It is shown that the total phase shift is directly proportional to the mass of the magnetization reversed zone, and hence to the volume of the defects. The dependence of the signal phase of the sensor on the mass of the metal in the sensor zone is obtained.

1. Introduction
The magnetization reversal of magnetic materials under the action of an alternating field occurs during the rotation and by the displacement of the domain boundaries [1, 2]. Changes in losses in magnetization reversal of metals can be evidence of accumulation of damage [3].

Figure 1. Magnetization loss sensor $W_1$ is the number of turns of the excitation winding; $I_1$, $U_1$ – current and voltage of the field winding.

The magnetization reversal sensor is a solenoid electromagnet with two poles and two windings: excitation and measuring. An alternating voltage is applied from the reference frequency generator to the excitation winding, and the voltage of the measuring winding is processed by an amplitude or phase method. Figures 1 and 2 show the device and the equivalent design of the sensor [4].
Figure 2. Equivalent calculation scheme $U_{me}$ is the magnetic potential drop in the electromagnet; $U_{mp}$ is magnetic potential drop in the product; $R_{p1}$, $R_{p2}$ are magnetic resistance of poles; $R_{jum}$ is magnetic resistance of the bridge; $R_p$, $R_5$ are magnetic resistance of the product and two gaps between the product and poles; $R_{F1}$ is magnetic resistance to the scattering flux; $M$ is the magnetomotive force of the excitation winding.

2. Methods

Equations of the product hysteresis loop backs and the electromagnet:

$$\Phi_p = \frac{U_{mp} - U_p}{R_p}$$  \hspace{1cm} (1)

$$\Phi_e = \frac{U_{me} - U_e}{R_e}$$  \hspace{1cm} (2)

Equations of magnetostatics:

$$\begin{cases} 
\Phi_e = \Phi_p + F_1 \\
U_p + \Phi_p \cdot R_p = F_1 \cdot R_{F1} = M + \Phi_e \cdot R_e \\
F_1 \cdot R_{F1} = U_p - \Phi_p \cdot R_5
\end{cases}$$  \hspace{1cm} (3)

After the transformation we obtain:

$$\Phi_e = \frac{U_{mp} - F_1 \cdot R_{F1} - \Phi_p \cdot R_5}{R_p} \cdot \frac{R_{F1} + R_e}{R_{F1} + R_e} + \frac{I_1 \cdot W_1 + U_{me}}{R_{F1} + R_e}$$  \hspace{1cm} (4)

Assuming the scattering flux $F_1$ to be a small quantity, we can assume that $\Phi_e = \Phi_p$. Then, after the transformation we obtain:

$$\Phi_e = \frac{U_{mp} \cdot C + B}{1 + \frac{R_5}{R_p} \cdot C}$$

where $C = \frac{R_{F1}}{R_{F1} + R_e}$, $B = \frac{I_1 \cdot W_1 + U_{me}}{R_{F1} + R_e}$.

Sensitivity of the sensor in the amplitude mode of stress processing:

$$\frac{d\Phi_e}{dR_p} = \frac{U_{mp} \cdot C}{R_p^2} \left( 1 + \frac{R_5}{R_p} \cdot C \right) + \frac{U_{mp} \cdot C + B}{R_p^2} + \frac{R_5}{R_p^2} \cdot C.$$

(7)
Figure 3. Vector diagram of currents and voltages.

The phase shift of the current \( I_2 \), and therefore of the output voltage \( U_2 \), is determined by two factors:

- a decrease in the angle \( \phi \) between the vectors \( U_1 \) and \( I_1 \) by an amount \( \Delta \phi_1 \), as a result of which the vector \( I_1 \) rotates counterclockwise, which causes the vector \( I_2 \) to rotate relative to point A counterclockwise;
- reduction of losses in the product \( I_C \), which leads to a rotation of the vector \( I_0 \) clockwise by an angle \( \Delta \phi_2 \).

Assuming the vectors \( I_1 \), \( I_2 \) and \( I_0 \) to be commensurate, changes in the angles \( \Delta \phi_1 \) and \( \Delta \phi_2 \) can be attributed to the vector \( I_2 \).

Assuming the triangle \( I_0, I_0', \Delta I_L \) to be rectangular:

\[
\Delta \phi_1 = \arctg \frac{\Delta L}{L} = \arctg \frac{L - L'}{L'},
\]

where \( L = \frac{W_1^2}{R_M} \).

Substituting the expression for the inductance \( L \) into equation (8), we obtain:

\[
\Delta \phi_1 = \arctg \left( 1 - \frac{R_e + R_p + R_s}{R_e + R_p + R_s + \Delta R_p} \right).
\]

As it can be seen, \( \Delta \phi_1 \) can vary from \( \arctg (1 - 1) = \arctg 0 \) to \( \arctg (1 - 0) = \arctg 1 \), or from 0 to 45 degrees. The greater phase sensitivity \( \Delta \phi_1 \) is, the smaller the magnetic resistance of \( R_M \) is.

Assuming that the triangle \( I_0, I_0', \Delta I_L \) is rectangular:

\[
\Delta \phi_2 = \arctg \frac{\Delta I_C}{I_0} = \arctg \frac{\Delta I_C}{\sqrt{I_C^2 + I_u^2}}
\]

Current loss in the product:

\[
I_C = \frac{P_C}{U_{CB}},
\]

where \( P_C \) is the total losses due to eddy currents and hysteresis.

\[
P_C = m \cdot p_e,
\]

where \( m \) is the mass of the remagnetizable part of the article and the core;

\( P_C \) is the loss in 1 kg of core and product.

\[
p_e = p_{10} \cdot B^n, \ W / kg,
\]

where:
\[ n = 5.691 \lg \frac{P_{1.5}}{P_{1.0}} \]

where \( P_{1.5} \) is the loss in 1 kg of steel at \( B = 1.5 \) T;
\( P_{1.0} \) is the loss in 1 kg of steel at \( B = 1.0 \) T;
\( B \) is the induction in the product, T.

Neglecting the voltage drop on the scattering inductance \( X_{S1} \), we take \( U_1 = U_{CB} \). Then we obtain:

\[ I_C = \frac{m \cdot p_{1.0} \cdot B^n}{U_1} \]

Let us find the increment of the current \( I_C \) from the change in the magnetization reversal losses:

\[ \Delta I_C = \frac{\Delta m \cdot p_{1.0} \cdot B^n}{U_1} \]

Assuming that the increment of \( \Delta I_C \) is small and the triangle is rectangular:

\[ \Delta \varphi_2 = \arctg \frac{\Delta m \cdot p_{1.0} \cdot B^n}{U_1 \cdot I_1} \]

Total phase shift:

\[ \Delta \varphi = \Delta \varphi_1 + \Delta \varphi_2 = \arctg \left( 1 - \frac{R_c + R_p + R_S}{R_c + R_p + R_S + \Delta R_p} \right) + \arctg \frac{\Delta m \cdot p_{1.0} \cdot B^n}{U_1 \cdot I_0} \]. \hspace{1cm} (10)

\[ \Delta \varphi, \ deg \]

\[ \Delta M, \ kg \]

**Figure 4.** Dependence of the phase of the sensor signal on the mass of the metal in the sensor zone.

It can be seen from Eq. (10) that the larger \( \Delta \varphi \) is, the smaller the total magnetic resistance of the chain is. Figure 4 shows the dependence of the sensor signal phase on the mass of the metal in the sensor zone. The total phase shift is directly proportional to the induction in the product and the mass of the remagnetized zone, and, hence, the volume of defects. Therefore, the magnetization reversal sensor can be used to detect structural defects and the continuity of materials [5-10].

3. Conclusion

A sensor for measuring magnetization reversal losses of ferromagnetic materials is investigated. A vector diagram of currents and voltages is constructed, in which the phase shift of the signal from the magnetization reversal losses is determined. It is established, that the phase shift of the current is due to two factors:

- reduction of the angle between the voltage and current vectors;
– reduction of losses in the product.

The dependence of the signal phase of sensor on the mass of the metal in the sensor zone is obtained. Expressions for the sensitivity in the amplitude and phase methods of signal processing on the magnetization reversal losses are obtained.

It is shown, that the total phase shift is directly proportional to the mass of the magnetic reversal zone, therefore, to the volume of defects.

Performed researches have shown that the magnetization reversal loss sensor can be used to detect material continuity defects.

References

[1] Vonsovsky S V 1971 Magnetism (Moscow: Nauka) p 1032
[2] Mishin D D 1981 Magnetic materials (Moscow: Higher School) p 335
[3] Mikheev M N, Ponomarev V S, Morozova V M, Remez N V, Deordiev G I 1987 About measurements of magnetization reversal losses at quality control of heat treatment Defectoscopy 12 72–74
[4] Vildanov R G 2004 Indicator of mechanical stresses IMN-1 Devices and technics of experiment 6 140–141
[5] Vildanov R G 2004 The indicator of mechanical stresses IMN-1 Measuring technique 3 31–33
[6] Khismatullin A S 2018 Automated software to determine thermal diffusivity of oil gas mixture J. of Phys.: Conf. Ser. 1015 052013
[7] Krivokoneva O O, Kudoyarov R I, Mavlekayev Ye Yu, Konys Ye M, Prakhov I V 2017 Life extension of oil transformers with long-term operation Bulletin YuUrGU. Energy Series [Vestnik YuUrGU. Seriya Energetika – in Rissia] 17(3) 60–66
[8] Mullakaev M S 2018 Ultrasonic intensification of the processes of enhanced oil recovery, processing of crude oil and oil sludge, purification of oil-contaminated water (Moscow: Research institute of history, economics and law) p 376
[9] Khusnutdinova I G, Bashirov M G 2017 The use of electromagnetic-acoustic method for estimating the stress-strain state of the metallic elements of power equipment Key Eng. Mat. 743 463–467
[10] Kuznetsov A V, Rebrovskaya D A 2018 Refinement of the model for estimating the reduction in power losses in the grid organization when compensating for reactive power in the consumer’s network Industrial Energy 10 31–36