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Electromagnetic sensor for the control of pipe wall thickness

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Abstract. Calculation of the primary inductive converter with magnetic core is problematic because of the difficulty in determining the various fluxes inside and outside the magnetic core. Observance of certain requirements for structural and scheme-related decisions makes is possible to substantially simplify theoretical expressions for description of work in such type of converters. The paper presents problems in the theory, design, and schematic layout of universal surface sensor with magnetic core, used for controlling wall thickness in tubular conductive products. The proposed construction of the sensor will allow using it to control wall thickness in a wide assortment of pipes.
Keywords: electromagnetic converter, sensor, magnetic flux, wall thickness, tubular product
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1. Introduction

Among the variety of converters, the sensors with ferromagnetic core having air gaps are often used. Changes in magnetic flux in the gap contain information about physical properties, thickness, and chemical composition of the product. The main advantage of these converters is their high sensitivity because the magnetic flux, which is concentrated in the gap, can reach significant values compared to the flows in other surface sensors for the same values of the exciting ampere-turns.

Calculation sensor without a magnetic core for the measurements of the characteristics of products at various configurations was considered in a number of papers [1, 2]. However, the results of these calculations for all practical purposes are difficult because the output signals of these converters have multiparameter information related not only to the measured characteristics of the products, but also to interfering factors, among which the main is air gap between the sensor and the product.

The change in the relative location of the sensor and the product has a significant effect on the output signals of converters. This fact substantially complicates the control.

Calculation of the primary inductive converter with a magnetic core is problematic because of the difficulty in determining the various fluxes inside and outside the magnetic core. Calculation is even more complicated when taking into account nonlinear character of magnetizing material of the magnetic core.

There are some calculation models [2] for such sensors, which to some extent take into account these factors, however, the final expressions of these works are so bulky that it is still far from practical application in the real conditions of production. It should be noted that the existing converters with a magnetic core are useful for the control of products of only one size. Observance of certain requirements for structural and scheme-related decisions makes it possible to substantially simplify theoretical expressions for description of work in such type of converters.

This is very important because the results of this theoretical substantiation can be applied to a universal sensor, which is used because of the design possibilities for research of the products of various configurations.

The paper presents problems of the theory, design, and schematic layout of universal surface sensor with a magnetic core, used for controlling the wall thickness in tubular conductive products.

2. The theory of the converter operation

Let us consider the inductive converter with open magnetic core to measure wall thickness in tubular products. Sensitivity of one sensor to the measured parameter is low. Two identical sensors were included in the differential scheme to increase the sensitivity and they were powered by the generator G (fig. 1). Operating OS and compensating CS sensors have two identical magnetizing and measuring coils, which are placed on the magnetic cores with gaps. Operating sensor is mounted on a test product TP, and compensating sensor is mounted on an exemplary product EP. The magnitude of the current in the magnetizing circuit is regulated by the resistance R_c and measured by the ammeter PA. The different signal of the electromotive force ΔE is measured by the voltmeter PV. Sign of the product's increment thickness is determined using a phase-sensitive voltmeter.

Figure 2 shows the location of magnetic cores of the operating and compensating sensors on the tubular product. Designations are given: $\Phi_{a\mp\Delta a}$, $\Phi_{a1\pm\Delta a}$ and Φ_{p1}

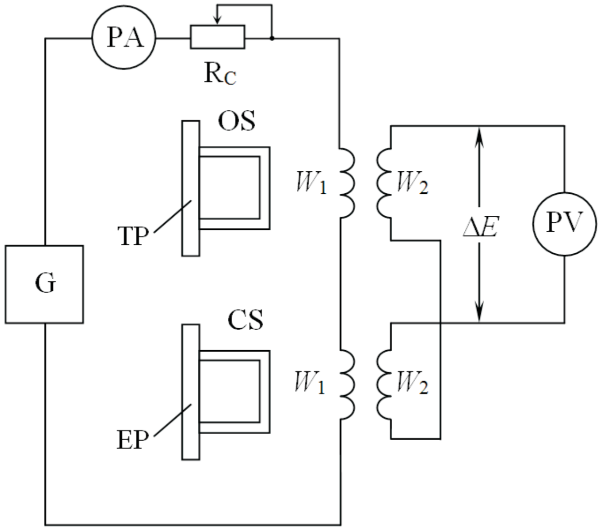

Fig. 1. Electric scheme showing inclusion of converters

— instantaneous values of fluxes in the test product, in the layer of air behind the product, and the scattering; Φ_a, Φ_{a1}, and Φ_{p2} — instantaneous values of fluxes in the exemplary product, in the layer of air behind the product, and the scattering; a and a_1 — thickness of the layer of the product and the air behind it, which limits the corresponding fluxes; Δa — change in thickness of the product; the signs $\mp$ correspond to a decrease and an increase in thickness of the product; b — thickness of the magnetic core; c — the distance between the poles of the magnetic core; d — width of the pole of the magnetic core.

$\Phi_{a\mp\Delta a} + \Phi_{a1\pm\Delta a}$ is the effective flux of the operating sensor, $\Phi_a + \Phi_{a1}$ is the effective flux of the compensating sensor. We have made the following assumptions. Effective magnetic flux will be determined by the magnetic resistance of the gap, rather

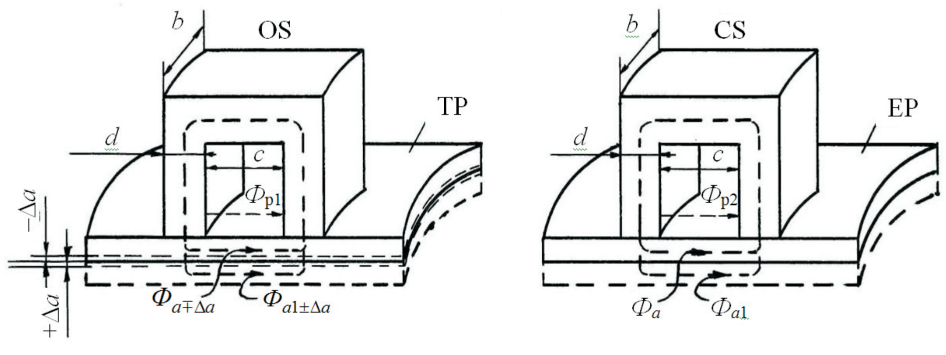

Fig. 2. The layout of magnetic cores of operating and compensating sensors on the tubular product

than resistance of the magnetic core because the air gap in the magnetic core is comparatively great. Besides the efficient flux, there are the fluxes of scattering, which are mutually compensated in differential mode of sensors. We assume that almost all the efficient fluxes are limited by the size of width of the pole of the magnetic core $d = a + a_1$. This is confirmed by experimental and theoretical data.

Expression for the instantaneous value of the difference EMF in the secondary windings sensor has the form:

$$\Delta e = -W_2 \frac{d\left(\Phi_{a\mp\Delta a} + \Phi_{a1\pm\Delta a} + \Phi_{p1} - \Phi_a - \Phi_{a1} - \Phi_{p2}\right)}{dt}. \tag{1}$$

Because the operating and compensating sensors are identical and included on the differential scheme, it can be assumed that the scattering fluxes are the same $(\Phi_{p1} = \Phi_{p2})$ and they are mutually compensated in expression (1). This relates to a non-magnetic product because the magnetic fluxes, which are associated with the eddy current are significantly lower than the scattering fluxes.

Using the results of work [3], the expressions for magnetic fluxes in the test and the standard samples and behind them are received. Expressions for them have an appearance:

$$\Phi_{a\mp\Delta a} = \frac{1}{\sqrt{2}} H_0 \mu_0 \mu_r \delta b \left[\sin\left(\omega t - \frac{\pi}{4}\right) - e^{-\frac{a\mp\Delta a}{\delta}} \sin\left(\omega t - \frac{\pi}{4} - \frac{a \mp \Delta a}{\delta}\right)\right], \tag{2}$$

$$\Phi_{a1\pm\Delta a} = (a_1 \pm \Delta a) H_0 \mu_0 \mu_r b e^{-\frac{a\mp\Delta a}{\delta}} \sin\left(\omega t - \frac{a \mp \Delta a}{\delta}\right), \tag{3}$$

$$\Phi_a = \frac{1}{\sqrt{2}} H_0 \mu_0 \mu_r \delta b \left[\sin\left(\omega t - \frac{\pi}{4}\right) - e^{-\frac{a}{\delta}} \sin\left(\omega t - \frac{\pi}{4} - \frac{a}{\delta}\right)\right], \tag{4}$$

$$\Phi_{a1} = a_1 H_0 \mu_0 \mu_r b e^{-\frac{a}{\delta}} \sin\left(\omega t - \frac{a}{\delta}\right), \tag{5}$$

H_0 — the average intensity of magnetic field in the air gap of sensor; μ_0 — magnetic constant ($4\pi \cdot 10^{-7}$ H/m); μ_r — the relative magnetic permeability of product; ω — the cyclic frequency; $\delta = \sqrt{2/\mu_0 \mu_r \delta\omega}$ — the depth of penetration of magnetic field in product; σ — the specific electric conductivity of material of product.

These ratios are received on the condition of equality of the relative magnetic permeability ($\mu_r = 1$) and the conductivities of materials of the test and the exemplary products.

It can be done in practice by means of selection of exemplary products for the value σ, corresponding specific electrical conductivity of the test product. If the dimensions of the product are large enough, then both sensors can be placed on it, but thickness of the product at location of the exemplary sensor must be known.

Using the results of work [3], the expression for the average value of magnetic field in the air gap of the sensor is obtained

$$H_0 = I_m W_1 \frac{b\left[0.26 + \frac{1}{\pi}\ln\left(1+\frac{2d}{c}\right)\right] + 2\left(0.077c + 0.25d\right)}{bd}, \tag{6}$$

I_m — the value of current in magnetizing circuit.

Substituting the values of magnetic fluxes (2-5) in expression (1), the formula for instantaneous value of the difference EMF has the form:

$$\Delta e = \omega W_2 H_0 \mu_0 \mu_r b e^{-\frac{a}{\delta}} \sqrt{M^2 + Q^2} \sin\left(\omega t + \operatorname{arctg}\frac{Q}{M}\right), \tag{7}$$

where

$$\begin{aligned} M = {} & e^{\pm\frac{\Delta a}{\delta}}\left(a_1 \pm \Delta a - \frac{\delta}{2}\right)\left(\cos\frac{a}{\delta}\cos\frac{\Delta a}{\delta} \pm \sin\frac{a}{\delta}\sin\frac{\Delta a}{\delta}\right) + \\ & + \cos\frac{a}{\delta}\cdot\left(\frac{\delta}{2} \mp \frac{\delta}{2}e^{\pm\frac{\Delta a}{\delta}}\sin\frac{\Delta a}{\delta} - a_1\right) + \frac{\delta}{2}\sin\frac{a}{\delta}\left(e^{\pm\frac{\Delta a}{\delta}}\cos\frac{\Delta a}{\delta} - 1\right), \end{aligned} \tag{8}$$

$$\begin{aligned} Q = {} & e^{\pm\frac{\Delta a}{\delta}}\left(\frac{\delta}{2} - a_1 \mp \Delta a\right)\left(\sin\frac{a}{\delta}\cos\frac{\Delta a}{\delta} \mp \cos\frac{a}{\delta}\sin\frac{\Delta a}{\delta}\right) - \\ & - \sin\frac{a}{\delta}\left(\frac{\delta}{2} \mp \frac{\delta}{2}e^{\pm\frac{\Delta a}{\delta}}\sin\frac{\Delta a}{\delta} - a_1\right) + \frac{\delta}{2}\cos\frac{a}{\delta}\left(e^{\pm\frac{\Delta a}{\delta}}\cos\frac{\Delta a}{\delta} - 1\right). \end{aligned} \tag{9}$$

Expressions (7-9) become considerably simpler, provided $\Delta a/\delta \ll 1$, that corresponds to little changes of thickness of test product compared to exemplary product or low frequencies of supply current.

In this case, the expression for effective value of the difference EMF takes the form [3]

$$\Delta E = \omega W_2 H_0 \mu_0 \mu_r b \Delta a e^{-\frac{a}{\delta}} \rho. \tag{10}$$

The quantity ρ calculated from the following relations, with decreasing thickness of the test product in relation to the exemplary product:

$$\rho = \frac{a_1}{\delta}\sqrt{\left(1+\frac{\Delta a}{a_1}\right)^2 + \left(1+\frac{\Delta a}{a_1}+\frac{\Delta a}{\delta}\right)^2}, \tag{11}$$

with increasing thickness of the test product in relation to exemplary product:

$$\rho = \frac{a_1}{\delta}\sqrt{\left(\frac{\Delta a}{a_1}-1\right)^2 + \left(1-\frac{\Delta a}{a_1}-\frac{\Delta a}{\delta}\right)^2}. \tag{12}$$

3. Experimental research

In order to determine the characteristics of the surface converters with magnetic core, experiments were carried out on tubular products.

For the measurement of increments in the product thickness, the sensors were used with the following parameters: $W_1 = 810$; $W_2 = 4000$; $d = 14\times10^{-3}$ m; $c = 14\times10^{-3}$ m; and $b = 19.8\times10^{-3}$ m. Measurements were done at the value of the magnetizing current 0.08 A. The average tenseness of magnetic field was 4963 A/m.

The samples were tubular products of duralumin alloy with the value of the electrical conductivity 1.72×10^{7} S/m. The tubular products had an outer diameter of $D = 0.146$ m.

With decreasing thickness of the test product in relation to the exemplary product, the thickness of the product was equal to 10^{-2} m and changed to the value Δa, which equalled 0.5×10^{-3} m; 10^{-3} m; 1.5×10^{-3} m; 2×10^{-3} m ; 2.5×10^{-3} m; 3×10^{-3} m. With increasing thickness of the product in relation to the exemplary product, Δa changed to the same value and thickness of the product $a = 6\times10^{-3}$ m.

The calculated curves of the output signal of the thickness of the tubular product during operation at 50 Hz, and the experimental results are shown in figure 3. Curves 1 are calculated for the case of decrease in the thickness of the test products in relation to the exemplary product, curves 2 — are calculated for the case of increase in the thickness of the test products in relation to the exemplary product. The results of experimentally obtained values of signals are marked for the cases: × — decrease in the thickness, ° — increase in the thickness. Analysis of the results allows concluding that small values of errors, which were obtained during the experiment, appear at relatively small variations in thickness. The experimentally obtained values of the errors when $\Delta a =\leq 10^{-3}\,\mathrm{m}$ for tubular products are 3.3%.

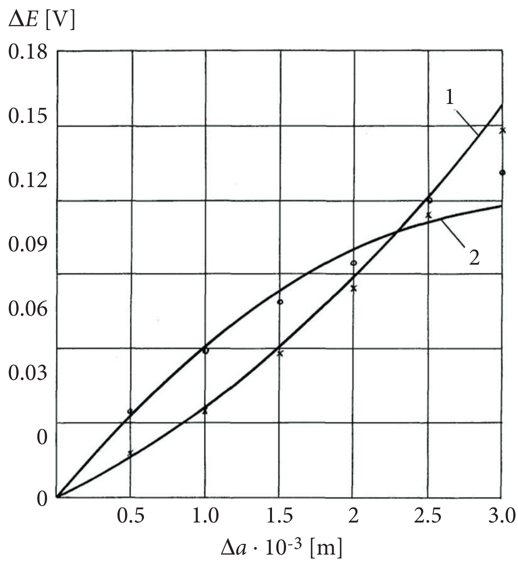

Fig. 3. The calculated curves and experimental values of difference EMF for various measurements of tubular products (× — experimental values of the signal with decrease in the thickness, ° — increase in the thickness)

To determine the thickness of cylindrical products, magnetic converters are made as a package of ferromagnetic plates that are free to move before contact with the surface of the test product [4]. Figure 4 shows an electromagnetic converter with W-shaped magnetic core located on the cylindrical surface of the product.

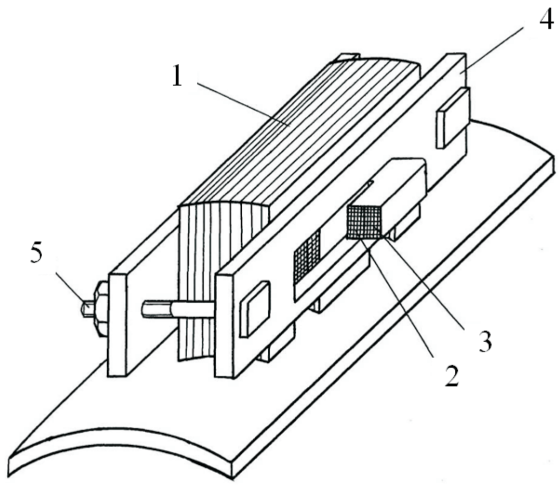

Fig. 4. Electromagnetic converter with W-shaped magnetic core

The sensor consists of a magnetic core 1 which is made as a packet of ferromagnetic plates, excitation coil 2, measuring coil 3, nonmagnetic metal plate 4, and clamping bolts with nuts 5.

The converter is installed on the test product, magnetic plate is adjusted to ensure its strip takes the form of the surface of the product, after which the plates of the magnetic core are fixed with coupling bolts and nuts. Figure 5 shows a photo of sensors on the test object.

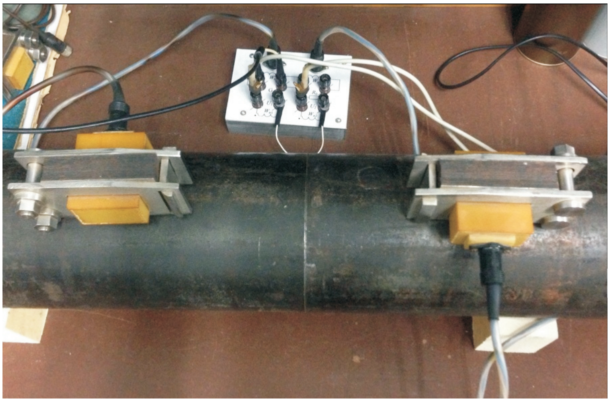

Fig. 5. Photo sensors on the tubular test object

4. The conclusions

Figure 3 shows that small values of errors, which were obtained during the experiment, appear for relatively small variations in thickness. The experimentally obtained values of the errors when $\Delta a =\leq 10^{-3}\,\mathrm{m}$ for tubular products are 3.3%. The proposed construction of the sensor will allow for using it to control wall thickness in a wide assortment of pipes.

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REFERENCES

[1] Gerasimov V., Ostanin Y., Pokrovsky A., *Non-destructive testing of product quality electromagnetic methods*, Moscow, Energiya, 1978.

[2] Polivanov K., *Theory of electrical engineering*, Moscow, Energiya, vol. 3, 1975.

[3] Gordon A., Slivinskaya A., *Electromagnets of direct current*, Moscow, Gosenergoizdat, I960.

[4] Sebko V., *Device for measuring the magnetic properties of ferromagnetic samples closed*, USSR Inventor's Certificate, № 1093997, 1984, Bul. № 19.

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Elektromagnetyczny czujnik do kontroli grubości ścianek rur

Streszczenie. Obliczenie podstawowego przetwornika indukcyjnego z rdzeniem magnetycznym jest problematyczne z powodu trudności w określeniu wewnętrznych i zewnętrznych strumieni rdzenia magnetycznego. Stosowanie pewnych wymagań dotyczących struktury i schematu przetwornika umożliwia zasadnicze uproszczenie teoretycznych wyrażeń opisujących pracę tego typu przetworników. Artykuł przedstawia problemy teorii i projektowania oraz schematyczny układ uniwersalnego czujnika powierzchni z rdzeniem magnetycznym stosowanego do kontroli grubości ścian elektroprzewodzących wyrobów rurowych. Proponowana konstrukcja czujnika pozwoli na zastosowanie go do szerokiego asortymentu rur.

Słowa kluczowe: przetwornik elektromagnetyczny, czujnik, strumień magnetyczny, grubość ścianki, produkty rurowe