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DETERMINATION OF THE OPTIMAL FREQUENCY OF THE PRIMARY MEASURING TRANSDUCER OF THE THICKNESS OF DIELECTRIC COATINGS OF METAL SURFACES

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Abstract. *The article provides an analysis of the physical processes underlying the operation of the measuring transducer, with a time based information presentation. A mathematical model is developed that describes the process of free oscillation attenuation excited in the LC-contour of primary measuring transducer, and analyzes and evaluates the influence of external factors that influence the measurement results. The ways of elimination of their influence on the results of measuring control are offered.*

Keywords: measuring, transducer, thickness, dielectric coating, metal surface, oscillation

WYZNACZANIE OPTYMALNEJ CZĘSTOTLIWOŚCI PIERWOTNYCH PRZETWORNIKÓW POMIAROWYCH DO POMIARU GRUBOŚCI POWŁOK DIELEKTRYCZNYCH NA POWIERZCHNIACH METALOWYCH

Streszczenie. *Artykuł zawiera analizę procesów fizycznych leżących u podstaw pracy przetwornika pomiarowego wraz z prezentacją informacji w czasie. Opracowano model matematyczny opisujący proces tłumienia drgań swobodnych wzbudzanych w obwodzie LC głównego przetwornika pomiarowego, analizujący i oceniający wpływ czynników zewnętrznych na wyniki pomiarów. Proponowane są sposoby wyeliminowania ich wpływu na wyniki kontroli pomiarów.*

Słowa kluczowe: pomiar, przetwornik, grubość, powłoka dielektryczna, powierzchnia metalu, oscylacja

Introduction

The basic principles of construction of measuring transducers, based on the excitation method in the electrically conductive basis of the measuring object of vortex currents, are described in [4, 5, 24]. The process of energy transfer in a oscillatory circuit can be of a different nature. Depending on the ratio of the active and characteristic (wave) contour resistance, the periodic (oscillatory) process can turn into aperiodic. But regardless of the nature of the transient process in the circuit, the time constant remains unchanged for certain parameters [14].

Since in a real oscillatory circuit, due to losses of accumulated energy for heating, free oscillations will always be attenuating; the main characteristic of the oscillatory circuit is the damping decrement, which is directly proportional to the active contour resistance and inversely proportional to the contour circuit's wavelength and its Q factor. The greater the active resistance of the contour, the smaller the time of attenuation of excited free fluctuations in it. The main energy losses in the circuit occur mainly in the active resistance of the coil, so the decay of the attenuation and the quality of the circuit will be determined by the quality factor of the coil of inductance [23, 26].

The equivalent circuit of the measuring transducer is shown in Fig. 1.

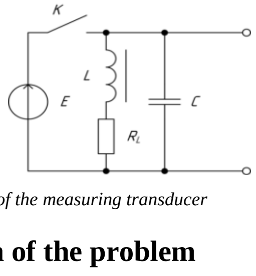

Fig 1. Equivalent circuit of the measuring transducer

1. Formulation of the problem

The change in the duration of the transition process in the circuit when applying the active component of the resistance in the form of a metal base of the object to be measured will depend on many factors. To increase the accuracy of measurement of such a time interval, it is necessary to ensure the maximum amplitude of the change in the damping time of free oscillations of the isolated circuit and the circuit that interacts with the object of measurement. One of the parameters that can be changed in a wide range without changing the hardware properties of the measuring transducer is the frequency of oscillations in the circuit. Therefore, the task of determining the optimal value of the oscillation circuit frequency is relevant, at which the maximum accuracy of measuring the attenuation time of free oscillations in the circuit can be achieved

2. Theoretical research

The total resistance of the inductor Z_{lss} coil will be determined as [25]:

$$Z_{lss} = Z_0 + Z_{md} = Z_0 + 2\pi f M\Psi(\beta,\gamma), \tag{1}$$

where Z_{lss} – the resistance of the coil; Z_0 – complete resistance in the absence of electromagnetic field conductive material; Z_{md} – additional resistance (introduced), which occurs when the coil of the conductive material appears; M – coefficient of co-induction (interaction) of a coil of inductance and conductive material; $\Psi(\beta,\gamma)$ – a function of flow coupling for a coil located normal to a flat conduct or plate with certain dimensions, conductivity and other parameters of the conductive material; β, γ – generalized parameters that characterize the geometrical and physical properties of the metal base of the control object.

The co-induction coefficient M is a functional dependence of the distance ℓ between the end of the core of the coil and the surface of the conductive material [6], which is described by the expression:

$$M = M_0 e^{-\frac{6l}{d_e}} \tag{2}$$

where M_0 – the coefficient of co-induction between the coil inductance and its mirror image at zero gap between the ends of their rods; d_e – equivalent diameter of the coil of inductance. For the convenience of calculations, the equivalent diameter value is taken to be equal to the average diameter of the coil. The value of the coefficient M_0 is determined from the ratio:

$$M_0 = \frac{e_1}{\dfrac{\Delta i_2}{\Delta t}} \tag{3}$$

where e_1 – the electromotive force of interinvitation, which arises in the first circuit with a uniform change in current at 1 amperes per second in the second circuit; i_2 – the current flowing along the second contour, with the first and second contours being inductively connected.

The value of the co-induction coefficient M_0 is determined experimentally under the following conditions: two coils of inductance L and L' having identical electrical, physical and geometric parameters, connecting the cores one of them is connected to the generator of the sinusoidal voltage through the resistor $R1$ (Fig. 2), which satisfies the condition:

$$R1 >> \sqrt{R_L^2 + (L \cdot \omega)^2} \tag{4}$$

where R_L – the active resistance of the inductance coil, L – the inductance of the input coil, ω – the angular frequency of the sinusoidal voltage. Another coil is connected to a voltmeter. The resistor $R2$ with a nominal resistance of about 10^3 Ohm for the load of the inductor L' is connected.

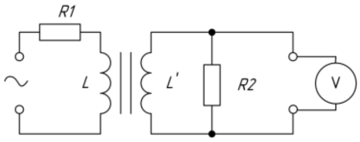

Fig. 2. Schematic diagram of the installation to determine the coefficient of co-induction between the coil and its mirror image

Using the scheme (Fig. 2), the expression for determining the coefficient of interinduction (3) can be rewritten as follows

$$M_0 = \frac{e_2 R1}{2\pi f U_0} \tag{5}$$

where e_2 – the electromotive force occurring in the second coil; $R1$ – the resistance, which specifies the current in the coil of the inductance; f – the frequency of the generator signal; U_0 – the amplitude value of the sinusoidal voltage of the generator. During the change of current Δt in the first circuit, the period of sinusoidal voltage e_1 was taken.

For a non-ferromagnetic plane conductor plate, the flow-coupling function $\Psi(\beta,\gamma)$ has the form

$$\Psi(\beta,\gamma) = -j\frac{2\beta^2 + th\frac{\gamma}{4}\sqrt{9 + j4\beta^2}}{3\sqrt{9 + j4\beta^2} + (9 + j2\beta^2)th\frac{\gamma}{4}\sqrt{9 + j4\beta^2}} \tag{6}$$

where $\beta = \frac{d_e}{2}\sqrt{2\pi f\mu\sigma}$; $\gamma = \frac{4h}{d_e}$; μ – the magnetic permeability of the plate; σ – specific electrical conductivity of the material of the plate; h – the thickness of the plate.

Substituting the equation (1), (3) and (6) in expression (1), we obtain the dependence for the complete resistance of the oscillatory circuit

$$Z_{вт} = Z_0 - j2\pi f M_0 e^{-\frac{6l}{d_e}}\frac{2\beta^2 + th(\frac{\gamma}{4}\sqrt{9 + j4\beta^2})}{\sqrt[3]{9 + j4\beta^2} + (9 + j2\beta^2)th(\frac{\gamma}{4}\sqrt{9 + j4\beta^2})} \tag{7}$$

To ensure the maximum sensitivity of the measuring transducer, it is necessary that the conductive object of a certain size, when approaching the inductance coil, contributes the maximum value of the full resistance to the contour. Since the circuit works in a resonant mode, the reactive component of the introduced resistance can be neglected [1, 27].

The expression for determining the time constant of free-fluctuation attenuation in the contour is written as follows [14]

$$\tau_k = \frac{2L}{Z_0 + Z_{вн}} = \frac{2L}{R_L + R_{вн}} \tag{8}$$

Performing the substitution in expression (8) of the above relations, we obtain an equation that describes the dependence of the time of attenuation of free oscillations excited in the LC-contour from the distance of the end of the core of the inductance coil to the conductive material of the control object's basis [2, 13].

$$\begin{aligned}\tau_k = &\left[-2L\frac{K}{R_L}\left(9 + 54P + 81P^2 + 4\beta^4 P^2\right)\right]\times \\ &\times\left(\begin{aligned}&-9K - 54KP - 81KP^2 - 4K\beta^4 P^2 + 4Y\beta^2 P^2\frac{K}{R_L} + 6Y\beta^2\sqrt{\frac{2K}{R_L} - 18} + \\ &+4Y\beta^4 P\sqrt{\frac{2K}{R_L} + 18} + 18\beta^2 P\sqrt{\frac{2K}{R_L} - 18}\end{aligned}\right)^{-1}\end{aligned} \tag{9}$$

where $K = R_L\sqrt{81 + 16\beta^4}$; $P = th\left(\frac{1}{4}\gamma\right)$; $Y = \pi f M_0 e^{-\frac{6l}{d_e}}$.

3. Experimental research

The analysis of equation (9) shows that the dependence of the decay time of free oscillations excited in the circuit from the distance l of the end of the inductor coil to the conductive basis of the control object has a nonlinear character. At the same time, the transformation function (9) has a plot with an approximate linear character, and if using elements of the oscillatory circuit with optimal parameters it is possible to create a measuring transformer with a transformation function that is close to linear in a definite range of variation of the distance from the end of the coil to electrical conductive basis of the object of control.

To conduct research, we will address the following characteristics of the object of measurement control [13, 15, 20]:

- thickness of dielectric coating ℓ , µm: 10 – 200;
- metal base material: steel grades 040A10, 1449-1HR, 1HR, 2HR, DC01, DD13;
- specific electrical conductivity of the base material σ, Sm/m: 6.8×10^6;

  The following parameters of inductance coils of the primary measuring transducer (L1, L2, L3) are used for the analysis:
- coil inductance is $122\cdot10^{-3}$ mH, $520\cdot10^{-3}$ mH, $1000\cdot10^{-3}$ mH;
- active resistance of coils 2.0 Ohm, 3.7 Ohm, 4.6 Ohm;
- the equivalent diameter of the coils is 7 mm, 8 mm, 9 mm.

For each coil, the value of the coefficient of interinduction M_0 was determined experimentally. To do this, an experimental installation was used, the principal scheme of which is shown in Fig. 2. The research was carried out in the frequency range of the generator of sinusoidal voltage from 5 kHz to 50 kHz. The averaged values of the experimental results for coils with different parameters in the form of the dependence of the coefficient of co-induction of the coil and its mirror image of the frequency of the supply voltage are given in Fig. 3. Significant change in the coefficient of interinduction is observed when the frequency of the supply voltage varies from 5 kHz to 50 kHz, so the theoretical study determined the average value of the M_0 coefficient from the specified frequency range of the supply voltage.

To determine the M_0 coefficient, the amplitude value of the voltage in the second circuit was determined from the results of the experiment (Fig. 2). The results are shown in Table 1.

Table 1. Amplitude values of the voltage in the second circuit when changing the frequency of the supply voltage from 5 kHz to 50 kHz

f, kHz	5	10	15	20	25
$e_2(L1)$, mV	25.0	25.0	30	32.5	35.0
$e_2(L2)$, mV	22.5	22.7	25.9	27.5	30.0
$e_2(L3)$, mV	21.3	22.1	24.8	27.0	29.0
f, kHz	30	35	40	45	50
$e_2(L1)$, mV	40.0	40.5	41.1	41.4	41.7
$e_2(L2)$, mV	35.0	35.2	35.8	36.1	36.3
$e_2(L3)$, mV	32.0	32.2	32.7	32.9	33.1

The graph of the change of the coefficient of interconnection M_0 from the frequency of the supply voltage is presented in Fig. 3.

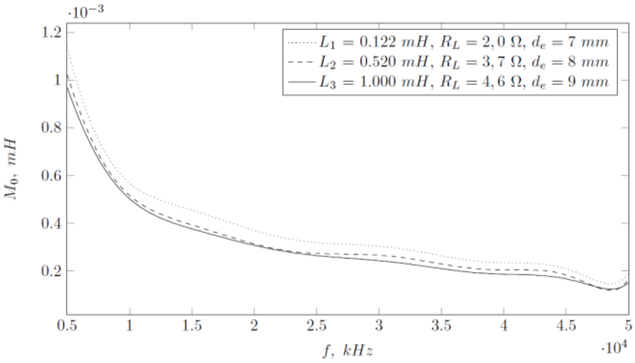

Fig. 3. Dependence of the co-induction coefficient of the coil and its mirror image on the frequency of the supply voltage

For theoretical studies, the mean value was chosen for the value of the co-induction coefficient. According to the results of the experiment, the following values of the coefficients of interinvitation were obtained [15, 22]:

- for L1, the coefficient of interinvection $M_0 = 0.40$ mH;
- for L2, the coefficient of interinvection $M_0 = 0.36$ mH;
- for L3, the coefficient of interinvection $M_0 = 0.34$ mH.

The choice of the optimum frequency of the measuring transducer was carried out provided that the primary sensitivity of the primary measuring transducer was maximized in the range of the change in the thickness of the dielectric coating from 0 μm to 200 μm. To ensure maximum sensitivity in the absence of external perturbing factors, it is necessary to ensure the maximum value of the introduced resistance when changing the thickness of the coating by 1%, and accordingly the maximum value of the increase in the time of attenuation of excited free oscillations. To determine the optimal frequency value, we obtain the following dependence [10, 21]

$$\delta(\mathrm{f}) = \tau_{\mathrm{k}}(\mathrm{f},\mathrm{l}) - \tau_{\mathrm{k}}(\mathrm{f},(\mathrm{l}\cdot 1.01)) \qquad (10)$$

and a definite argument of the function at which it acquires the maximum value [11, 16].

Theoretically, the values of the optimal frequency were determined for different thicknesses of the basis of the control object h (0.18 mm, 0.22 mm, 0.36 mm) [8] at various values of the parameters of the inductance coils of the measuring transducer [3, 9, 12, 17–19]:

- inductance of coils L1 – $122\cdot 10^{-3}$ mH, L2 – $520\cdot 10^{-3}$ mH, L3 – $1000\cdot 10^{-3}$ mH;
- active resistance of coils R1 – 2.0 Ohm, R2 – 3.7 Ohm, R3 – 4.6 Ohm;
- the equivalent diameter of the coils $d1_e$ – 7 mm, $d2_e$ – 8 mm, $d3_e$ – 9 mm.

For conducting theoretical investigations, the magnetic permeability of the base material (steel grade 040A10, 1449-1HR, 1HR, 2HR, DC01, DD13[20]) was taken into account as 600 objects by known practical studies [7, 23], which determine the physical and chemical properties of steel for annealing temperature in the range of 0–200°C set the initial and maximum permeability respectively $\mu_i = 400$ and $\mu_m = 650$. Specific electrical conductivity of the material of the basis of the object of control was determined on the basis of the known value of the specific resistance ρ of the 08КП alloy at a temperature of 20°C $\rho = 147\times 10^{-9}$ Ω·m and assumed to be equal to 6.8×10^{6} cm/m.

4. Conclusions

The given data of theoretical studies testify that the optimum frequency of the oscillatory circuit of the measuring transducer depends on the parameters of the inductance coil of the measuring transducer. So, for an inductor of a primary converter of $122\cdot 10^{-3}$ mH, the frequency from the range 170 - 400 kHz can be considered optimal. As the inductance increases to $1000\cdot 10^{-3}$ mH, the optimal frequency will increase, and the optimal value will be within the range of 340–750 kHz. At the same time, the absolute value of the gain of the decay time of oscillations also depends on the parameters of the inductance of the oscillatory circuit and increases with increasing its inductance. So, when using the inductance L1 = $122\cdot 10^{-3}$ mH, with an equivalent diameter of the coil of 7 mm, the absolute value of the gain of the oscillation decay time is 260 μs. With an increase in inductance to L3 = $1000\cdot 10^{-3}$ mH, this gain will be 720 μs.

Obviously, for the control of objects with different thickness of the metal base, it is advisable to use one type of inductance at different frequency values, since the change in the increase in the oscillation decay time for the range of change in the thickness of the base 0.18–0.36 mm for one inductance will be: for L1 $122\cdot 10^{-3}$ mH – 4%; for L2 $520\cdot 10^{-3}$ mH – 3%; for L2 $1000\cdot 10^{-3}$ mH – 3%. At the same time, the difference in the attenuation time for different inductances at the same frequency (350 kHz) at best would be 55% for L1 and L2, in the worst case for L1 and L3 at the same frequency would be 68%.

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