On the one-point calibration of eddy current phase transducers on example of zinc coating thickness gauges

Vladimir A. Syasko, Irina V. Pilatova
Constanta Ltd, PO box 89, St-Petersburg, 198095, Russia,
tel. +78123722903, e-mail: office@constanta.ru

Adam Polacek
NDT1 Kraft Ltd, Krymská 238/18, 101 00 Prague 10, Czech Republic,
tel. +420 777 944 957, e-mail: info@ndtone.com

Abstract

It is interesting to measure thickness of non-ferromagnetic coatings on electrically conductive ferromagnetic basis using eddy current phase three-winding probe. Known principles of balance provide a possibility to suppress influence of a gap, radius and product surface roughness deviation. However, when the same type of metal coating is applied to the metal substrates with different magnetic permeability and electrical conductivity the calibration of known techniques involves making coating thickness reference specimens of all metals to be used as bases for products. The paper gives a theoretical analysis of the measurement tasks and shows that there are algorithms of measurement information change and calculation of correct calibration curves in the whole range of measurement using only single-point calibration on sample of metal base without coating. The basic theoretical principles, the algorithms of calibration and measurement, as well as the results of the practical implementation and testing of the eddy current phase three-winding probe with the electromagnetic thickness gauge K5G are presented in the paper.

Metallic coatings received by electrochemical (galvanic) methods have a wide range of application at engineering enterprises. The most prevalent metallic coating is zinc coating. Its prevalence is caused by the following reasons:
- high natural resistance, because of creation of protective foils of corrosion products on zinc in a corrosion environment;
- high anodity of steel protection in atmospheric conditions and in fresh water in temperatures up to 70^{o}C.
- high technology of coatings receipt and relative low cost;

Service life of a zinc coating is determined first of all by its thickness T_c. Eddy current phase method of metallic coating thickness measurement is based on analysis of interaction of own electromagnetic field of primary measuring transducer with the electromagnetic field of eddy currents induced in the controlled object and depending on controlled parameter T_c and obstructive parameters: coating conductivity σ_c and basis conductivity σ_b, basis magnetic permeability μ_{bas}, product geometrical characteristics (diameter d, surface roughness R_z and others) and also magnitude of gap h between metallic coating and transducer contact surface.

Electronic circuit of transformer three-winding eddy current phase transducer that uses as a support signal voltage on compensative winding is shown on fig. 1. The transducer shown on fig. 2 is made in a small cylindrical body and is connected to the electronic unit with a cable that serves both as power supply and channel connection UART14400.

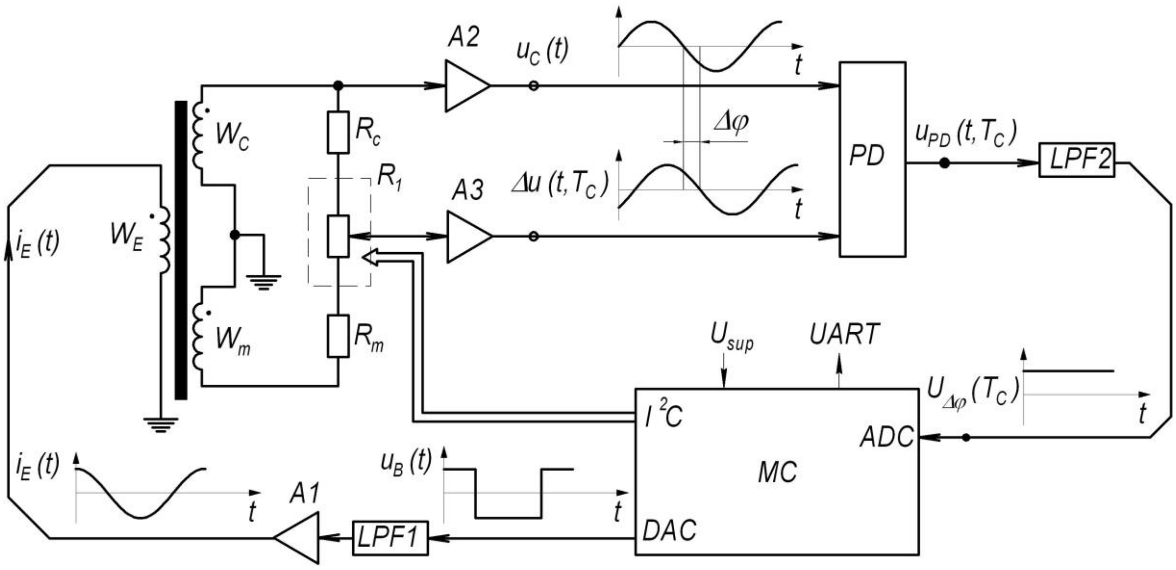

Figure 1. Electronic circuit of eddy current phase transducer: A1-A3 – amplifiers, PD – phase detector, LPF1 – LPF2 – low-pass filters, W_E – excitation winding, W_C and Wm – differentially connected compensative and measuring winding, MC – microcontroller, R1 – controlled digital balancing potentiometer

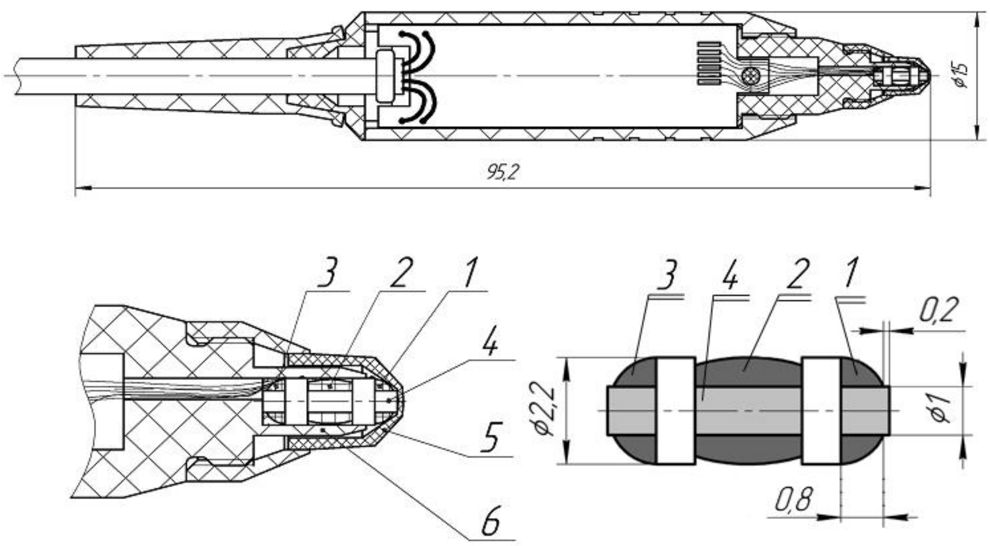

Figure 2. Eddy current phase transducer with miniature sensitive element and exchangeable protective cap: *1* – measuring W_M, *2* – excitation W_E and *3* – compensative W_C windings, *4* – ferrite core, *5* – protective cap, *6* - housing

The design of sensitive element that has dimensions close to minimum technologically possible dimensions with determined diameter of ferrite core ensures equivalent radius of excitation winding $R \approx 1.5$ mm. The ferrite core is protected from wear with exchangeable protective cap that is moulded from glass-filled polymer. The contact surface of the cap is quasi spherical. The elements of electronic circuit are also situated on the printed circuit board that is installed inside the transducer body.

The winding W_E is excited by sinusoidal current $i_E(t)$ of frequency f. Amplified differential (induced) voltage $\Delta u(t, T_c)$ comes to phase detector PH. As a supportive signal is applied voltage $u_c(t)$ at the output of compensative winding W_c. The direct voltage $U_{\Delta\varphi}$ at the output of low-pass filter is proportional to the phase difference $\Delta\varphi$ of voltage $u_{c(t)}$ and $\Delta u(t, T_c)$. Balance of the transducer windings is carried out by use of digital potentiometer controlled by microcontroller. The electronic circuit shown ensures measurement error $\Delta\varphi$ less than $\pm$ 0,05^o. The maximum frequency of excitation current is 3.7 MHz

It is convenient for ease and simplification of described sensitive elements of considered eddy current transducers to use a generalised parameter of eddy current control as follows:

$$\beta = R\sqrt{2\pi f \mu_r \mu_0 \sigma} \qquad (1)$$

where R – equivalent radius of excitation winding; σ – material conductivity; μ_0 – magnetic constant; μ_r - relative magnetic permeability of material (for non-ferromagnetic materials $\mu_r = 1$).

When the parameters of eddy current transducer are consistent, for tasks of thickness measurement of metallic non-ferromagnetic coatings with conductivity σ_c (zinc, chrome, cadmium, etc.) on ferromagnetic steels with conductivity σ_b the generalised parameter will change from $\beta_b = R\sqrt{2\pi f \mu_r \mu_0 \sigma_b}$ when $T_c = 0$ to $\beta_c = R\sqrt{2\pi f \mu_r \mu_0 \sigma_c}$ when $T_c = \infty$.

The depth of penetration of eddy currents is $\delta = R\sqrt{2}/\beta$. Expression $T_{cmax} = 1/\sqrt{\pi f \mu_0 \sigma}$ can be used for close evaluation of maximum measured thickness of non-ferromagnetic conductive coating.

The dependence of relative complex induced voltage $\Delta\mathring{U}^* = \Delta\mathring{U}/|\Delta\mathring{U}(\mu_b = \infty, T_c = 0)|$ on controlled and obstructive parameters while measuring thickness of zinc coating on steel bases with the transducer with excitation frequency f = 0.2 MHz and equivalent radiuses of windings R = 1.5 mm will be analyzed. The dependence is shown on fig. 3.

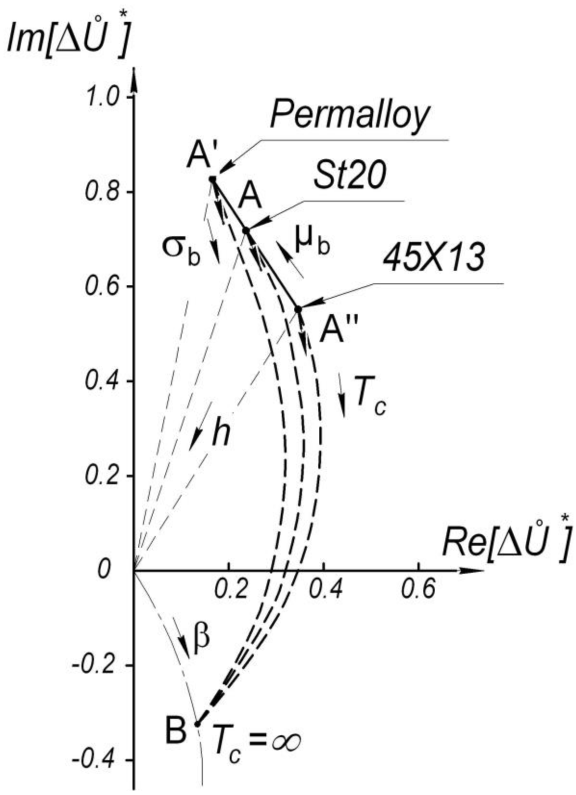

Figure 3. Dependence of relative complex induced $\Delta\mathring{U}^*$ on controlled and obstructive parameters.

Arc AB on fig. 3 shows hodograph $\Delta\mathring{U}^*$ with increasing thickness of coating from zero (point A) to T_{cmax} (point B, corresponding to $T_c >> \delta$).
When h increases, hodograph $\Delta\mathring{U}^*$ for balanced transducer will practically represent straight line coming to starting point of the coordinates. The balance of transducer according to known principles enables to suppress the influence of deviation h on the phase of differential voltage in needed range.

Hodograph $\Delta\mathring{U}^*$ is indicated by A'A" line with change of magnetic permeability of steel basis. The point A' corresponds to maximum magnetic permeability (electrical steel, permalloy) and point A" is minimum magnetic permeability (high carbon alloyed ferromagnetic steels).

Change of σ_b also influences $\Delta\mathring{U}^*$. Electrical conductivity deviation of steel in range of a lot of products can reach 3 ... 10%, however because of its small absolute value (≈ 1 … 3 MS/m), its influence on measuring results can be neglected.

The dependence of informative parameter $\Delta\varphi(T_c)$ for the analysed case is shown on figure 4.

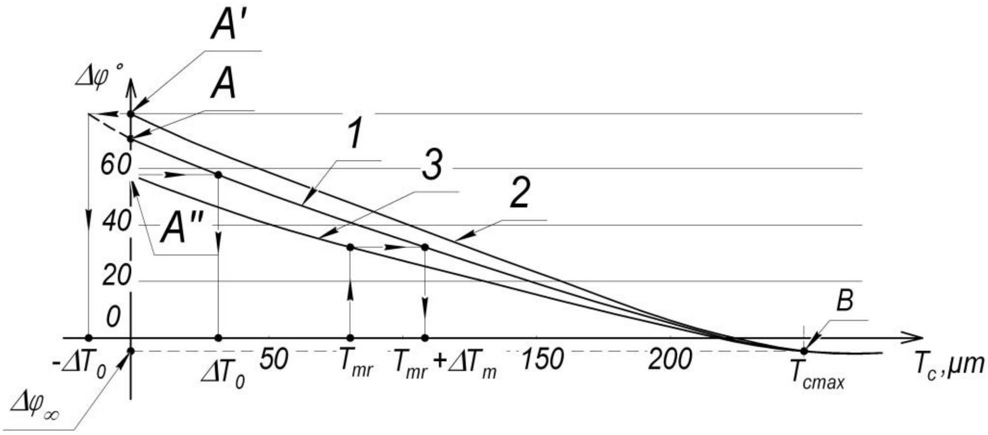

Figure 4. Dependence $\Delta\varphi(T_c)$ of zinc coating on steel bases (1- St20, 2 – permalloy, 3 – 45X13).

The curve shown on figure 4 represents calibration characteristics of eddy current phase transducer received on zinc coating thickness reference specimens while the basis is made of steel St20.

If the coating is applied on steel with the magnetic permeability that is different from magnetic permeability of steel St20, the point corresponding to $T_c = 0$ will shift (range of shift from A' to A") and point B corresponding to the calculated result T_{cmax} will remain practically unchanged. A change of transducing characteristics will occur, which will lead to the additional measurement error $\Delta T_c(\mu)$.

To avoid this additional measurement error in accordance with existing measuring methods it is necessary to perform calibration procedure of measuring transducer. Currently, leading European manufacturers regulate two-point calibration of eddy current phase transducers including two steps:

- excluding additive component of measurement error ΔT_0 by setting “zero” on product sample without coating;
- excluding multiplicative component of measurement error (ΔT_0 - ΔT_m) by setting the upper measurement limit while using certified full-scale metallic coating thickness reference specimens T_{mr} on basis from product material.

While applying this calibration method the actual thickness coating T_{ca} is equal to:

$$T_{ca} = T_{res} + \frac{\Delta T_0 - \Delta T_m}{T_{mr}} T_{res} - \Delta T_0 \quad \text{...} \quad (2)$$

where T_{res} – metallic coating thickness measurement result on product using calibration characteristics. Such method provides quite satisfactory results. However, for calibration it is necessary to manufacture full-scale coating thickness reference specimens practically for all materials of basis used in manufacturing process. A significant enlargement of specimens range and also high costs considering necessity of their certification make process of implementation of measuring instruments in enterprises difficult and slow.

The offered method of one-point calibration (setting of zero) of eddy current phase transducers while using special calculation algorithm enables to avoid presented disadvantage. The principle of the method as was described above consists in the fact that to the maximum measured thickness T_{cmax} corresponds a unique result $\Delta\varphi_{\infty}$, practically independent of magnetic permeability of basis under the condition that σ is constant value (fig. 3, 4). For zinc coating when f = 0.2 MHz and R = 1.5 mm $T_{cmax} \approx$ 250 μm.

The one-point calibration algorithm will be analysed for the case when the product's basis magnetic permeability μ_{bas} is less than magnetic permeability of steel St20 used for manufacturing of zinc coating thickness specimens, on which the calibration characteristics were created. One-point calibration is performed according to the following algorithm. While setting up the probe on tested product without coating and performing measurement we receive a measurement result different than zero ΔT_0. As a second point to calculate correction coefficients we will use calculated result T_{cmax}. In this case during measurements the actual coating thickness result T_{ca} will be calculated using formula:

$$T_{ca} = T_{res} + \frac{\Delta T_0}{T_{cmax}} T_{res} - \Delta T_0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3)$$

For the analysed case with this calibration method $\Delta T_c(\mu) < \pm (0{,}01 T_c + 1)$ μm in controlled thickness measurement range up to 100 μm, which is not worse than in above described two-point calibration method.

It also should be mentioned that while using as basis thickness reference specimens made of steel St20 in case when the product's basis has magnetic permeability $\mu_{bas} > \mu_{St20}$ an uncertainty occurs while setting zero because in the area of negative thicknesses the device does not have real calibration characteristics, which also causes measurement error (fig. 4). This implies that basis for sets of coating thickness reference specimens shall be made of steel with $\mu_b \geq \mu_{bp}$ for all products.

Use of the offered calibration method avoids a necessity to manufacture sets of full-scale coating thickness reference specimens, which considerably lowers working and economic costs to prepare a set of measuring instruments and gives a significant effect at manufacturing enterprises with a wide variety of manufactured coating and basis products. The offered approach for production of coating thickness reference specimens and analysed calibration method found a practical realisation while manufacturing and using multifunctional coating thickness gauge of galvanic coatings „Konstanta K6" and a set of eddy current phase transducers PH.