

# Electromagnetic thickness measurement of coatings. Situation and prospects.

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## Abstract

Currently, the leading aircraft manufacturing, shipbuilding and engineering enterprises apply a wide range of protective coatings: dielectric, metallic ferrous and metallic non-ferrous single-layer and multiple layers in various combinations. The questions of application of magneto-inductive, eddy current frequency, eddy current phase and eddy current amplitude-phase methods for measuring coating thickness  $T$  in conditions of modern high-technology manufacturing environments characterized by wide measurement range (from few micrometers to 150 mm), wide range and variations of physical, mechanical and geometrical characteristics of used materials and standard sizes of products are presented in the paper. Based on performed analysis of the measuring methods, circuits of measuring transducers, informative and obstructive parameters and also measurement techniques it is demonstrated that reliability and repeatability of measurement results required by current and prospective normative documentation are quite often not ensured, especially at the edges of measurement ranges. Interference-protective test methods of receiving and processing measurement information, circuits that realize them, principles of manufacturing and certification of full-scale coating thickness reference specimens and also new methods of calibration and measurements suppressing influence of obstructive parameters and definitely ensuring measurement error  $\pm(0,01T+0,001)$  mm for considered protective coatings are described and analysed in detail. Examples of application of developed electromagnetic coating thickness gauges and transducers are presented in the paper.

**Keywords:** NDT-wide, thickness gauge, coating, electromagnetism, coating thickness, measurement

The problem to ensure reliability and safety of engineering, shipbuilding, aviation, rocketry and power engineering products considering increasing demands and economical effectiveness in condition of tough competition of manufacturers and companies using the products is becoming increasingly important.

Strict conditions of operation, influence of high and low temperatures, cyclic and brief loads (including impact), various aggressive substances, including atmospheric, put high requirements to protective coatings that determine a wide range of applied materials and technologies of their application. In addition, the effectiveness of coating application is assessed as a complex of functional properties (anticorrosive, decorative, wear-resistant, etc.) throughout coating service life and the coating thickness  $h$  is considered as defining functional parameter.

Analysis shows that for the most tasks of measuring  $h$  in present productions is possible through use of electromagnetic methods based on eddy current and magnetic non-destructive testing. The positive feature of these methods is a possibility to apply them in one-side approach in workshop and outdoors, sufficient locality, high accuracy and reliability.

A wide range of coatings of the most various materials are used as coatings, their thickness  $h = 0.2 \mu\text{m} - 150 \text{ mm}$ . The general parameters that characterise coatings can be distinguished as follows: relative magnetic permeability  $\mu$ , electrical conductivity  $\sigma$ , hardness  $HC$  or microindentation hardness  $HV$ , single layer or multiple layers (considering that layers have different  $\mu$ ,  $\sigma$  and  $HC$ ), density  $\rho$ , surface roughness  $R_z$ , temperature  $t$ . Stability and deviation of these characteristics and similar characteristics of substrates within controlled product or

group of analogical products are very important. Geometrical characteristics radius  $r$  and dimensions that can vary from miniature to large sized have also great influence. Based on the selected parameters characterising coatings and substrates and also all products in general the tasks of coating thickness inspection can be formulated and examples of these tasks can be presented.

Ferrous conductive coatings on conductive ferrous substrates. The given group of tasks concerns electrolytic nickel coating thickness measurement on products from ferrous metals.

Nonferrous conductive coatings on conductive ferrous substrates. The given group of tasks concerns coating thickness measurement of the most of galvanic coatings (chrome, zinc, copper, etc.), carbon fiber reinforced polymers, plated coatings on products from ferrous metals.

Dielectric coatings on conductive ferrous substrates. The given group of tasks concerns thickness measurement of lacquer and paint, bituminous, powder, plastic, fiberglass and other coatings on products from ferrous metals, thickness measurement of reinforced concrete and rebar.

Ferrous conductive coatings on conductive nonferrous substrates. The given group of tasks concerns thickness measurement of electrolytic nickel on products from nonferrous metals.

Nonferrous conductive coatings on conductive nonferrous substrates. The given group of tasks concerns thickness measurement of tin and copper coatings on nonferrous metals and others.

Dielectric coatings on conductive nonferrous substrates. The given group of tasks concerns thickness measurement of conversion, lacquer, paint, plastic and fiberglass coatings on products from nonferrous metals, lacquer and paint coatings on carbon fiber reinforced polymers and others.

Ferrous conductive coatings on dielectric substrates. The given group can be considered a task of thickness measurement of ferrous conductive material (e.g. foil from electrolytic nickel) of sheet or complex shape.

Nonferrous conductive coatings on dielectric substrates. The given task can be considered as a task of thickness measurement of nonferrous conductive material (e.g. foil from chrome) of sheet or complex shape.

Dielectric coatings on dielectric substrates, for example rubberlike thermo-protective coatings on products from fiberglass.

Often rise a situation while coatings have to ensure parameters that exclude one another or they cannot be fully accomplished using single layer coating. For example the requirements of corrosion resistance increased significantly along with the necessity of ensuring attractive appearance, shock resistance and ensuring corrosion resistance after chips of lacquer and paint coatings. To ensure these requirements multilayer coating is created on metal - surface is treated by special reagents at the beginning, afterwards multiple layers are applied on product. Multilayer coatings ensure heat resistance, corrosion resistance and in many cases radiation protection.

Analysis of normative documentation and literature resources enables to distinguish main objectives of separate layers thickness measurement of multilayer coatings:

- conductive nonferrous substrate - conversion and dielectric lacquer and paint coatings;
- conductive ferrous substrate - conductive nonferrous and dielectric coating;
- conductive nonferrous substrate - conductive nonferrous and conductive nonferrous coatings;
- conductive ferrous substrate - conductive nonferrous and conductive ferrous coatings.

Each objective has its characteristic features, however, the biggest issues traditionally emerge while measuring on a few microns thick coatings, especially metallic due to scale factor and a large number of obstructive parameters determined by characteristics of coatings and substrates described above.

The current situation of electromagnetic control on an example of protective metallic coating thickness measurement as the most actual will be analysed. All normative documents impose the condition of guaranteed assurance of set value of coating thickness. A significant part of coatings materials is costly and has small thickness - from 2 to 20 ... 40  $\mu\text{m}$ . Increase of measurement accuracy and respective tightening of technological tolerances ensure substantial cost savings.

Thickness measurement of metallic nonferrous coatings upon ferrous substrates and ferrous coatings on nonferrous and dielectric substrates with good surface roughness shall be performed optimally with use of magneto-inductive thickness gauges. Eddy current phase thickness gauges enable to perform thickness measurement of metallic ferrous and nonferrous coatings on ferrous products with surface roughness up to  $R_z \approx 40 \dots 60 \mu\text{m}$  and also on small-sized parts. Thickness measurement of metallic nonferrous coatings on nonferrous substrates is possible by application of eddy current frequency method.

The operating manuals of coating thickness gauges apply term *accuracy*  $\Delta(h)$ .

Generally is used in two  $\Delta(h)$ :

- $\Delta(h) \leq \pm (ah + b)$ , where  $a$  – is multiplicative coefficient,  $b$  – random error component determined by transducer and microcontroller characteristics;
- $\Delta(h) \leq \pm ah$  or  $\Delta(h) \leq \pm b$ , in dependency, which value is larger.

Currently, in the production programme of the most of the leading manufacturers appeared metallic coating thickness gauges with claimed  $\Delta(h) \leq \pm (0,01h + 1) \mu\text{m}$  in range of small thicknesses.

It should be considered that the claimed dependencies  $\Delta(h)$  imply use of the devices in normal conditions on sample substrates and coating thickness reference specimens, with use of which the procedure of calibration characteristic creation was received (functional dependency between measured  $h$  and output code  $N(h)$  of measuring transducer). It can mislead users about measurement reliability in manufacturing conditions and add a significant ambiguity in results assessment.

The analysis of claimed and actually ensured metrological characteristics of protective metallic coating thickness gauges will be presented.

Metrological characteristics are defined by measurement method, design of measuring transducers, applied transducing algorithm and computation of thickness value according to calibration characteristic. Complex of informative and obstructive parameters acting on measuring transducers in processes of calibration characteristic creation, calibration and measurements substantially influences these processes. They can be split in geometrical and physical. The geometrical parameters: coating thickness  $h$ , substrate thickness  $T$ , diameter of measured area  $D$ , surface curvature radius  $r$  and surface roughness  $R_z$ , distance from edge (edge effect). Physical parameters: conductivity  $\sigma$ , permeability  $\mu$ , coercive force, thermoelectric effect, temperature  $t$ , external electromagnetic fields, vibrations.

## **Influence of geometrical obstructive parameters.**

### ***Surface roughness and surface curvature.***

Eddy current phase transducers ensure tune out from gap influence  $Z$  during measurements that practically entirely avoids influence of deviation  $r$  and  $R_z$  up to value approximately 40  $\mu\text{m}$  with appropriate settings.

The additional measurement error for magneto-inductive and eddy current frequency transducers during measurements of metallic coatings considerably depends on  $Z$  and equivalent gap  $Z^*$  determined by product radius  $r$ .

During measurement of metallic coating thickness by magneto-inductive and eddy current frequency transducer on substrates with regular surface roughness the displayed values variation is approximately  $\pm R_z/5$ . It means random component of additional measurement error, during measurements with averaging, determined by  $R_z$ , does not exceed value  $\Delta(R_z) \leq \pm R_z/(5\sqrt{n})$ , where  $n$  – is a number of averaging for measurements in set area on product. For example when measuring zinc coating thickness on steel substrate with magneto-inductive transducer while the substrate was exposed to sandblasting with  $R_z = 25 \mu\text{m}$ , with  $n = 5$ ,  $\Delta(R_z) \leq \pm 2 \mu\text{m}$ .

During measurement in range of small thicknesses on cylindrical products with radius  $r$  the additional measurement error  $\Delta(r)$  has additive character. For transducers with  $D = 1.5 \dots 3 \text{ mm}$   $\Delta(r) \approx (200 \dots 220)r^{-1,07}$ , where  $r$  – mm,  $\Delta(r)$  –  $\mu\text{m}$ . For example with change of  $r$  from 10 to 7.5 mm  $\Delta(r)$  will change from  $\sim 9 \mu\text{m}$  to  $\sim 12 \mu\text{m}$ .

### ***Diameter of measured area and edge effect***

Sensitive elements of primary transducers are designed with outer shields from soft magnetic steels for magneto-inductive transducers and high-frequency ferrites for eddy current transducers. In addition, it can be claimed that  $D$  is practically equivalent to transducer shield diameter and minimum distance from shield to an edge of a flat product, when there is no additional measurement error, can be considered equivalent to  $(0.1 \dots 0.2)D$ .

### ***Substrate thickness***

One of the main characteristics of substrate is its minimum thickness  $T_{\min}$ , not influencing measurement result. For high frequency eddy current transducers  $T_{\min} \approx 2.5/(\pi f \mu_0 \sigma)^{1/2}$ , where

$\mu_0$  – magnetic constant,  $\sigma$  – conductivity of inspected object,  $f$  – transducer excitation frequency. For low frequency magneto-inductive transducers  $T_{\min} \approx (0.3 \dots 0.4)D$ .

## **Influence of physical obstructive parameters**

### ***Conductivity of substrate and coating when measuring conductive nonferrous coatings on conductive nonferrous substrates.***

Eddy current phase transducers are designed with self-oscillating circuit, their output frequency depends on induced inductance. Variation of substrate conductivity  $\sigma_2$  of actual production from nonferrous metals can reach  $\Delta\sigma_2 \approx \pm(0.05 \dots 0.1)\sigma_2$ . For metals and alloys with conductivity 9 – 60 MSm/m with  $h < 20 \mu\text{m}$  and equivalent transducer winding radius  $R \approx 1.5 \text{ mm}$  it will lead to variation of induced inductance approximately  $\Delta L_{\text{in}} \approx \pm(0.012 \dots 0.025)L_{\text{in}}$ . Due to this the measurement error for metallic coating thickness measurements will reach  $\Delta h(\sigma) \approx \pm 1.2 \mu\text{m}$  for  $\sigma_2 \approx 60 \text{ MSm/m}$  and  $\Delta h(\sigma) \approx \pm 2 \mu\text{m}$  for  $\sigma_2 \approx 9 \text{ MSm/m}$ .

Eddy current phase transducers are most often designed with three winding circuit with differentially connected measuring and compensative windings. It is possible to perform measurements with coating conductivity  $\sigma_1 \gg \sigma_2$  (for example copper or silver on brass) if using eddy current phase transducers.

Change of substrate conductivity when  $\sigma_2 \approx 10 \text{ MSm/m}$  on  $\pm 1 \text{ MSm/m}$  will lead to measurement error of copper or silver coating ( $\sigma_1 \approx 60 \text{ MSm/m}$ ) approximately  $\Delta h(\sigma) \approx \pm(1.5 \dots 2) \mu\text{m}$  when measuring coatings with thicknesses up to  $h = 30 \mu\text{m}$ .

### ***Substrate permeability while measuring conductive nonferrous coatings on ferrous substrates.***

Informative parameter of magneto-inductive two-winding transformer transducers - change of flux linkage  $\Psi(h)$ , penetrating the measuring (secondary) winding, is inversely proportional to  $h$  and directly proportional to  $\mu_2$  (measurement error does not depend on substrate and coating conductivity):

$$\Psi(h) = \Psi_0 + \Psi_{\text{in}}(h),$$

where  $\Psi_0$  – flux linkage when  $h = \infty$ ;  $\Psi_{\text{in}}(h)$  – induced flux linkage. A local variation of magnetic properties is characteristic for steels. In addition, variation of permeability  $\mu_2$  of steel substrates exposed to quenching and machining is bigger than in magnetic soft steels. For magnetic soft steels the variation  $\mu_2$  within a sample with diameter around 50 mm will reach 10 – 20 %. For alloyed steels exposed to quenching and polishing the variation  $\mu_2$  can reach 40 – 50 %.

For examination of influence  $h$  and  $\mu_2$  on flux linkage of small sized transducers, was calculated parameter  $\Psi^*(h) = (\Psi_0 + \Psi_{\text{BH}}(h)) / \Psi_0$  of measuring winding by method of finite elements. In range of small thicknesses for transducer with diameter of measured area  $D = 3 \text{ mm}$  local variation of magnetic properties in range  $\pm 50 \%$  regarding to the mean value will lead to deviation of showed values from minus 1.5 to + 0.7  $\mu\text{m}$ . Such deviation will be significantly bigger (from 1.5 to 4  $\mu\text{m}$  depending on material grade) for alloyed steels with smaller  $\mu_2$ .

## ***Temperature***

The most of the operating manuals for protective coating thickness gauges contain information about operating temperature from minus 10 to + 40 °C. Temperature influence was studied for thickness gauges of leading manufacturers of coating thickness gauges in range from -20 to +40 °C. In range of small coating thicknesses were received coefficients of additional error component  $\Delta h(t)$ , determined by temperature influence, for thickness gauges: 'K5' (Czech Republic) - 0.06  $\mu\text{m}/^\circ\text{C}$ , 'Elcometer 456' (United Kingdom) – 0,13  $\mu\text{m}/^\circ\text{C}$  and 'Positector 600' (USA) – 0,38  $\mu\text{m}/^\circ\text{C}$ . It means that with 10 °C change of temperature  $\Delta h(t)$  will be approximately 0.6  $\mu\text{m}$  – for 'K5', 1.3  $\mu\text{m}$  – for 'Elcometer 456', 4  $\mu\text{m}$  – for 'Positector 600'.

## ***External electromagnetic fields.***

Their sources are power units (interferences with frequency 50 or 100 Hz), transducers of motor controllers (pulsed interferences with kHz frequencies) and communication equipment (high frequency interferences). The variation of shown values can be higher than admissible measurement error in area of influence of the fields. Reduction of their influence can be reached only by measuring with averaging.

## **Calibration characteristic**

Calibration characteristic of thickness gauges transducers is presented as a function, calculated automatically according to codes  $N(h)$  received on coating thickness reference specimens.

To ensure  $\Delta(h) \leq \pm (0,01h + 1) \mu\text{m}$  it is optimal to approximate the calibration characteristic by polynomial  $N(h) = kh^3 + mh^2 + nh + p$  with groups with 4 points within the whole number of points. The values of coating thickness reference specimens shall be chosen from sequence 0; ~ 5 ... 10  $\mu\text{m}$ ; ~ 16 ... 20  $\mu\text{m}$ ; ~ 30  $\mu\text{m}$ ; ~ 40  $\mu\text{m}$ ; ~ 60  $\mu\text{m}$ ; ~ 80  $\mu\text{m}$ ; ~ 100  $\mu\text{m}$ ; ~ 125  $\mu\text{m}$ ; ~ 150  $\mu\text{m}$ ; ~ 175  $\mu\text{m}$ ; ~ 200  $\mu\text{m}$ ; ~ 250  $\mu\text{m}$ . For this range coefficients  $k$ ,  $m$ ,  $n$  and  $p$  are calculated from four groups. In addition, approximation error  $\Delta_a(h)$  will be negligibly small in the range of small thicknesses. Accordingly, with trusted probability  $P = 0,99$  in the range of small thickness with  $\Delta(h) \leq \pm 1 \mu\text{m}$  the coating thickness reference specimens for calibration characteristic shall be made and verified with accuracy  $\pm 0,3 \mu\text{m}$ .

## **Creation of calibration characteristic and control of transducers of coating thickness gauges**

Creation of transducers calibration characteristic is most often carried out on coating thickness reference specimens made of metallic materials in normal conditions. As standards are used coating thickness specimens in range from 2 to 1000  $\mu\text{m}$ . The limit of absolute measurement error during manufacture and verification of working standards is  $\Delta_{ws}(h) \leq \pm ((0,1 \dots 0,3) + 0,025h) \mu\text{m}$ . Substrate of the coating thickness reference specimen must have thickness more than  $T_{\min}$ . Currently, profilographic method is used most often to verify (calibrate) step coating thickness reference specimens that ensures  $\pm (0,1 \dots 0,2) \mu\text{m}$  accuracy in range of small thicknesses. However, the method puts tough limits on parallelism of sides of substrates.

Sometimes it is not possible to manufacture metallic coating thickness reference specimens as their characteristics would not meet the actual ones due to many causes. In such situation the coating thickness reference specimens are made of samples from actual production according to the metallographic method or calowear method. The calowear method accuracy in small thickness range is  $\Delta h_c \leq \pm(0,1 \dots 0,3) \mu\text{m}$ . Its benefit is in the fact there are no requirements to parallelism of substrate sides that are necessary if using optical gauging. Physical characteristics of coating thickness reference specimens and substrates materials should be selected in accordance with measuring method used in specific thickness gauge.

Polished steel substrates should be selected carefully before applying coating when manufacturing metallic reference specimens for magneto-inductive and eddy current phase thickness gauge. The substrates with thickness more than  $T_{min}$  should have variation  $\mu_{sub} = \mu/\mu_{max}$ , ensuring variation of 'zero' in small thicknesses range maximum  $\pm(0.1 - 0.3) \mu\text{m}$ . The coating thickness specimens have to be demagnetized.

Nonferrous metals requiring hand finishing can be used as substrates when manufacturing coating thickness reference specimens for eddy current and phase thickness gauges. Substrates with thickness more than  $T_{min}$  selected for manufacture of reference specimens have to have variation  $\sigma_2$  not more than  $\pm(0.3 - 0.5) \text{MSm/m}$ . The coatings shall be applied in just prepared electrolyte according to the technologies corresponding to the ones applied in manufacturing process where the device will be used.

Constant temperature of specimens  $t = (20 \pm 2) ^\circ\text{C}$  should be kept during creating of calibration characteristic and verification processes and also ensure a level of electromagnetic fields as low as possible.

Fulfilment of the presented conditions during manufacturing and verification of coating thickness reference specimens, approximation of calibration characteristic and conditions of creating calibration characteristic ensure  $\Delta h \leq \pm(0,01h + 1) \mu\text{m}$  in range of small thicknesses in normal conditions.

Research of an average service period of metallic coating thickness reference specimens by means of multiple measurements by magneto-inductive thickness gauge showed that up to 3000 - 5000 measurements practically do not change the characteristics of metallic coatings.

## **Calibration and measurements**

User's calibration of coating thickness gauges shall be carried out before performing measurements using working standards - coating thickness reference specimens of various combinations of substrate and coating materials that are grouped according to their purpose with admissible absolute manufacturing error  $\Delta_{ws}(h) \leq \pm((0,2 \dots 0,3) + 0,05h) \mu\text{m}$ .

Often, coating imitations, foils from polyethylene terephthalate, put on product specimens without coating are used for calibration of magneto-inductive coating thickness gauges in range of small thicknesses. Minimum thicknesses of imitators based on PET foils are approximately 5 - 10  $\mu\text{m}$ . By selection of the foils a thickness variation of  $\pm 0,3 \mu\text{m}$  can be reached in area diameter of approximately 6 - 10 mm. Foils shall be replaced after 30 - 200 measurements (in dependency on imitator thickness) to avoid influence of their wear.

During measurements of conductive nonferrous coatings on ferrous and nonferrous substrates with use of eddy current transducers the amount of coating thickness reference specimens can be disappointingly large. In the present time, leading manufacturers deal with this issue in the following way. They insert nonvolatile memory in the transducer and store 'coating-substrate' calibration characteristics in the memory. The calibration characteristics are received on coating thickness reference specimens. The measurement accuracy  $\Delta h$  depends practically additively on influence of substrate parameters in range of small thicknesses and is avoided by setting 'zero' on product sample without coating.

Practically all influencing factors determined by parameters of coating, substrate and environmental conditions affect measuring transducer in calibration and measurement processes. Considering the above mentioned local variation of substrate  $\mu_2$  for magneto-inductive and eddy current phase thickness gauges causes variation of values approximately  $\pm(1 - 3) \mu\text{m}$  in range of small thicknesses; change of temperature on  $10^\circ\text{C}$  can lead to measurement error  $0,5 - 3 \mu\text{m}$ ; wear of imitators can determine uncontrolled measurement error during calibration. Eddy current frequency and phase thickness gauges are highly affected by variation of substrate  $\sigma_1$  and coating  $\sigma_2$  (possible up to  $\pm(1 - 2) \mu\text{m}$ ). It is recommended to carry out calibration and measurements with averaging in the area of inspection or within production lot to decrease influence of  $\sigma_2$ ,  $\mu_2$  and  $R_z$  variations.

The analysis that was done shows the following.

The thickness gauges manufactured and used in industry in the present day and also documented methods of their application cannot ensure measurement accuracy  $\Delta h \leq \pm(0,01h + 1) \mu\text{m}$  that is claimed in operating manuals in conditions of technological variations of physical and geometrical parameters of products and environmental conditions of the most of the engineering manufacturing plants.

Accredited metrological services should be equipped with coating thickness reference specimens of needed combinations of coatings and substrates materials - working standards made according to unified technology in accordance with the engineering documentation corresponding to inspected products to carry out verification in range of small thicknesses.

Measurements with averaging in set inspected area or within defined amount of products with mentioned obstructive parameters enable to receive thickness value that characterizes technological process of coating thickness application with suppression approximately  $\sqrt{n}$  times the variation of values determined by obstructive parameters. When  $n = 10 \dots 15$  it can be considered that the measurement of technological thickness of metallic coatings is carried out for analysed measurement methods with  $\Delta h \leq \pm 2 \mu\text{m}$  in range of small thicknesses with trusted probability  $P = 0,95 \dots 0,99$ , what is confirmed by operation experiences with the devices.

Main problems observed during thickness measurements of dielectric coatings of general purposes in range up to  $500 - 2000 \mu\text{m}$  are in range of small thickness when measuring on sand blasted and grit blasted substrates with  $R_z = 40 - 60 \mu\text{m}$  and on products with small radius. It can also be claimed that accuracy  $\Delta h \leq \pm(0,01h + 1) \mu\text{m}$  cannot be ensured in many cases.



Main issues observed during measurements of thick coatings (in range 20 - 150  $\mu\text{m}$ ) are connected with the necessity to ensure locality of measurement, especially can be claimed that for the most of the transducers in range of large thicknesses measurement area diameter is significantly larger than transducer diameter.

Other up-to-date problems:

- avoiding (significant decrease of) wear of core surface of the magneto-inductive transducers leading to change of calibration characteristic and emergence of substantial additional measurement error. The wear can be lowered by application of quenched cores with hardness up to 65 HRC with nonferrous super hard sprayed coating and development of creating pulsed magnetic field principles different from harmonic sinusoidal and also use as primary informative parameter areas induced by EMF along with test methods of primary measuring information processing excluding their magnetizing and influence of temperature instability

- decreasing of measured area of magneto-inductive transducers without decreasing of sensitivity and range of measurement by optimization of magnetic system and development of group of geometrically and electrically similar sensitive elements;

- development of shielded magneto-inductive transducer design with symmetrical magnetic system ensuring measurements with its non-perpendicular position regarding to the product;

- development of transducing algorithms ensuring full tune out of eddy currents influence that are created in metallic coatings and substrates and also suppression of pulsed and power-supply interferences for magneto-inductive thickness gauges by developing algorithms of creating pulsed magnetic field different from harmonic sinusoidal, synchronous with period of line voltage and also use as primary informative parameter area of induced EMF with time of integration longer than time of pulsed eddy currents existence;

- development of eddy current phase primary measuring transducers with built-in electronics of excitation current frequency up to 40 MHz, ensuring value of generalised information parameter  $\beta \approx 2 \dots 20$  with equivalent excitation winding radius  $\approx 1 \dots 3$  mm, enabling measurements of metallic coatings thickness on small sized products from ferrous metals;

- development of eddy current phase transducer with excitation current frequencies up to 4 MHz, ensuring value of generalised information parameter  $\beta \approx 2 \dots 20$  with equivalent excitation winding radius  $\approx 1 \dots 3$  mm and also algorithm of its balancing and selection of point of count, enabling thickness measurements of coatings from nonferrous metals on small sized products from ferrous metals in measurement range 2 ... 5  $\mu\text{m}$ ;

- development of eddy current phase-amplitude transducer with excitation current frequencies up to 4 MHz, ensuring value of generalised information parameter  $\beta \approx 2 \dots 20$  with equivalent excitation winding radius  $\approx 1 \dots 3$  mm and methods of measurement of two layers coating (zinc / lacquer and paint coating) on ferrous conductive substrates;

- development of normative documents and principles connecting thickness measurement results of galvanic coatings, actual value of coating conductivity and conductivity of pure metal of coating and protective properties by means of implementation of concept "thickness measurement result of galvanic metallic coating with defined value of pure metal conductivity" analogically to the concept of "ultrasonic thickness of product wall or standard samples";

- analysing the question of implementation of concept of "primary standard of galvanic metallic coatings with known value of conductivity" and their real realization;
- development of single-point calibration methods ensuring tune out from influence of conductivity and permeability in large range of thickness measurement of metallic and dielectric coatings, what will enable to significantly reduce amount of coating thickness reference specimens while using devices and will simplify preparation procedures of devices before measurements;

All these questions will be analysed in detail in the paper on specific theoretical and experimental results of works accomplished by members of the firm.