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**TEST DESK FOR EDDY-CURRENT PROBE CHECKING**

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**Abstract.** *The paper presents a test desk and the results of the experiment on the validity of the "Eddy-current probe – control object" system mathematical model. The "Eddy-current probe – control object" system mathematical model takes into account finite control object dimensions and its face of curvature absence. The paper focuses on the influence of the control object diameter and the distance from Eddy-current probe to Control object on the Eddy-current probe relative inductance curve dependence.*

**Keywords:** eddy current probe, eddy current probe model, test desk.

**Introduction**

With ultrasonic processes control quality demands are rising, the necessity to raise the Ultrasonic Oscillator (USO) parameters quality measurement is arises. The basic USO parameter is mechanical amplitude oscillation. Mechanical amplitude measurement sensors quality determines measurement quality [1], which, in case of eddy-current probe, is determined by material parameters, face concentrator vibrations velocity and its dimensions. The free area to measure mechanical oscillations as mentioned in [2] remains a significant issue.

It is generally known that sensors accuracy and sensitivity determine the control quality, which urge further research to raise not only accuracy of measurements but also make the measurements simple. The approximate "Eddy-Current Probe – Control Object" (ECP – CO) system mathematical model is taking into account the control object dimensions that has been developed to determine the free area size influence on ECP impedance [3].

**Problem statement**

A test desk and experimental data are presented. Experimental data are collected, on the basis of the ECP behavioral inductance dependency on distance from ECP to CO, that is, CO radial dimensions influence the steepness and ECP nonlinearity inductance curve on distance from ECP to CO, which proves the "ECP – CO" system mathematical model [3] validity. It takes into account the edge effect influence on accuracy and ECP sensitivity, which are used for USO mechanical amplitude measurement.

**Eddy-Current Probe Model**

As a result of theoretical research "ECP – CO" system mathematical model was built:

$$\dot{Z}_{add}(a_1, \Delta a, b_1, \Delta b, R_{ob}, h, N, v) = j\omega\pi \times \mu_1 \mu_0 k_p(R_{ob}) \dot{F}(a_1, \Delta a, b_1, \Delta b, R_{ob}, h, N, v), \quad (1)$$

where

$$\begin{aligned} \dot{F}(a_1, \Delta a, b_1, \Delta b, h, N, v) = & \sum_{p=1}^N \sum_{t=1}^N \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{\mu_2 q_{nm1} - \mu_1 \dot{q}_{nm2}}{\mu_2 q_{nm1} + \mu_1 \dot{q}_{nm2}} \times \\ & \left( \frac{k_1 \sin^2(0.25\lambda_{nx}(a_1 + p\Delta a)) \sin(0.5\lambda_{ny}(b_1 + t\Delta b))}{\lambda_{nx} \|\sin(\lambda_n x)\|^2 \|\sin(\lambda_n y)\|^2} + \right. \\ & \left. \frac{k_2 \sin^2(0.25\lambda_{ny}(b_1 + p\Delta b)) \sin(0.5\lambda_{nx}(a_1 + t\Delta a))}{\lambda_{ny} \|\sin(\lambda_n x)\|^2 \|\sin(\lambda_n y)\|^2} \right) \times \\ & \times e^{-2q_{nm}h}; \end{aligned}$$

$$\lambda_{nx} = \frac{n\pi}{pa(0.5a_1 + N\Delta a)};$$

$$\lambda_{my} = \frac{m\pi}{pb(0.5b_1 + N\Delta b)};$$

$$pa > 1, pb > 1;$$

$$q_{nm1} = \sqrt{\lambda_{nx}^2 + \lambda_{ny}^2 + k_{v1}^2};$$

$$k_{v1} = -0.5\mu_1\mu_0\sigma v;$$

$$\dot{q}_{nm2} = \sqrt{\lambda_{nx}^2 + \lambda_{ny}^2 + k_{v2}^2 + j\omega\mu_2\mu_0\sigma};$$

$$k_{v2} = -0.5\mu_2\mu_0\sigma v;$$

$$\|\sin(\lambda_{nx}x)\|^2 = \int_0^{pa(0.5a_1+N\Delta a)} \sin^2(\lambda_{nx}x)dx;$$

$$\|\sin(\lambda_{ny}y)\|^2 = \int_0^{pb(0.5b_1+N\Delta b)} \sin^2(\lambda_{ny}y)dy;$$

$$k_1 = \sin\left(\lambda_{my} \frac{b_1 + p\Delta b}{2}\right) \times \sin^2\left(\lambda_{nx} \frac{a_1 + t\Delta a}{4}\right) / \lambda_{nx};$$

$$k_2 = \sin\left(\lambda_{nx} \frac{a_1 + p\Delta a}{2}\right) \times \sin^2\left(\lambda_{my} \frac{b_1 + t\Delta b}{4}\right) / \lambda_{my};$$

$$\dot{k}_p(R_{ob}) = \frac{\dot{I}_{rk}(R_{ob}) + \dot{I}_{rb}(R_{ob})}{I_r};$$

$$\dot{I}_{rb}(R_{ob}) = 4 \int_{-\infty}^0 dz \int_0^{\frac{\pi}{2}} d\varphi \int_0^{R_{ob}} r j_{sd}(r, z, \varphi) dr;$$

$$j_{sd}(r, z, \varphi) = -j\omega\mu_2\mu_0 H_0(R_{ob}, z, \varphi) \times \frac{I_1(kr)}{kI_0(kR_{ob})};$$

$$k = \sqrt{-j\omega\mu_2\mu_0\sigma};$$

$$H_0(R_{ob}, z, \varphi) = \frac{1}{\mu_1\mu_0} \text{rot}(\dot{A}_{2-0}) \Big|_r = R_{ob};$$

$$\dot{I}_r = \int_{-\infty}^0 dz \iint_S j_r(x, y, z) dx dy;$$

$$\dot{I}_{rk}(R_{ob}) = 4 \int_{-\infty}^0 dz \int_0^{\frac{\pi}{2}} d\varphi \int_0^{R_{ob}} r j_r(x, y, z) dr d\varphi;$$

$$\dot{J}_r(x, y, z) = -j\omega\sigma\dot{A}_{\varphi 2}(x, y, z),$$

where  $a_1, \Delta a, b_1, \Delta b$  is rectangular pancake inner lengths and pancake pitches on x and y coordinates, accordingly;

$R_{ob}$  is CO radius;

$h$  is distance from pancake to CO;

$N$  is pancake turns number;

$v = \omega_{ok} A_{ok}$  is CO movement velocity along longitudinal axis relatively to the pancake (in the sinusoidal CO vibration case);

$\omega_{ok}, A_{ok}$  is CO circular frequency and amplitude oscillation, accordingly;

$\omega$  is ECP source current circular frequency;

$\mu_1, \mu_2$  is medium relative permeability, in which the pancake is placed and CO relative permeability, accordingly;

$$\mu_0 = 4\pi 10^{-7} \text{ Hn/m};$$

$\sigma$  is CO electrical conductivity;

$\dot{A}_{2-0}, \dot{A}_{\varphi 2}$  is field response vector-potential and vector-potential in the infinite CO or in the CO with the radial dimension much more greater than the pancake maximum radial dimension, accordingly;

$J_1$  is 1st kind 1st order Bessel function;

$I_0, I_1$  is 1st kind 0th and 1st order modified Bessel functions, accordingly.

### Test desk description

To check the validity of “ECP – CO” system mathematical model (1), a Measurement Device (MD) prototype was constructed, which flow diagram is depicted on fig. 1, and ECP was made, which represents a square pancake on PCB.

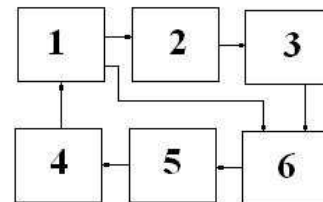


Fig. 1. Measurement device flow diagram:

1 – VCO;

2 – PBF;

3 – parallel oscillatory circuit with ECP;

4 – microcontroller;

5 – LPF;

6 – XOR

The ECP was made like a square spiral, because this pancake construction provides less reflected impedance compared to the circular spiral pancake construction with the same inductance value. This pancake construction allows to decrease MD transfer function nonlinearity (fig. 2).

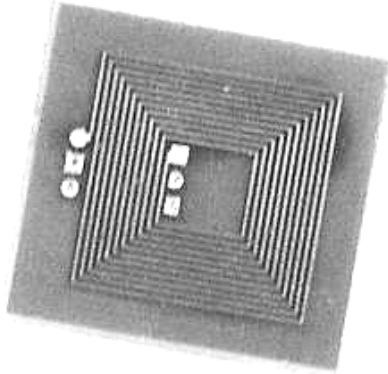


Fig. 2. Eddy-Current Probe

The MD transfer function nonlinearity is caused by parallel oscillatory circuit resonance frequency inverse quadratic dependence on ECP inductance and its Phase Transfer Function (PTF) nonlinearity in the case of large resonance frequency deviation.

The MD main part presents amplitude modulator on the generator working in key mode [4], which consists of a Voltage Control Oscillator (VCO) built on Microchip (MC) ON Semiconductor firm 74HC4046. The MC controls the bipolar transistor 2SD1859. The MD also contains Pass-Band Filter (PBF), which consists of a serial resonance circuit and parallel resonance circuit. Parallel resonance circuit contains ECP and voltage from it is delivered to the Analog Device firm comparator ADCMP600 input, whose output goes to XOR circuit input built in MC 74HC4046, and is compared with the VCO output. VCO output frequency is controlled by Atmel firm microcontroller Mega8535, with the purpose to control working point on MD PTF. The microcontroller also measures differential amplifier (not depicted on fig. 1) output and its non-inverting input is connected to the Low-Pass Filter (LPF). And finally, microcontroller depicts the measurement results on 7-segment 3-digit indicator (also not depicted on fig. 1). VCO frequency is equal 1 MHz.

The test desk consists of CO, motionlessly fixed by a nip and moveable ECP, which is attached to a rod moved by a micrometer 5451 – 0.01. The ECP is placed parallel to CO face thus forming “ECP – CO” system. 7, 8 and 9 mm diameter steel drills were used as COs.

### Measurement device flow diagram

As a result of connecting ECP to parallel resonance circuit, the ECP sensitivity raises [5], due to current resonance. Turning parallel resonance circuit into a close-to-resonance mode provides the parallel resonance circuit ability of working in the PTF linear part with the biggest steepness [6]. Operation on high frequencies decreases reflected active component impedance, which, as it is known, decreases with the ECP source current frequency increases [7], and also facilitates stability by a figure of merit, and thus improving measurement accuracy [8]. The estimated PTF nonlinearity does not exceed 3% in MD working range, that allows to neglect induced distortions to ECP inductance dependence on the distance from ECP to CO, that is, the further estimation of edge effect influence on ECP inductance dependence on distance from ECP to CO needs no experimental data corrections, as it depicts ECP inductance behavior when the basic and interfering parameters change.

### Experiment

The purpose of the developed “ECP – CO” system mathematical model was to reveal edge effect influence on ECP inductance dependence on distance from ECP to CO. Twenty, sixteen and nine trial experiments corresponding to 9, 8 and 7 mm in diameter COs have been carried out. After the data statistic processing, the experimental dependencies of ECP reduced inductance on the distance from CO were established with the distance of ECP from CO of 1 mm (fig. 3).

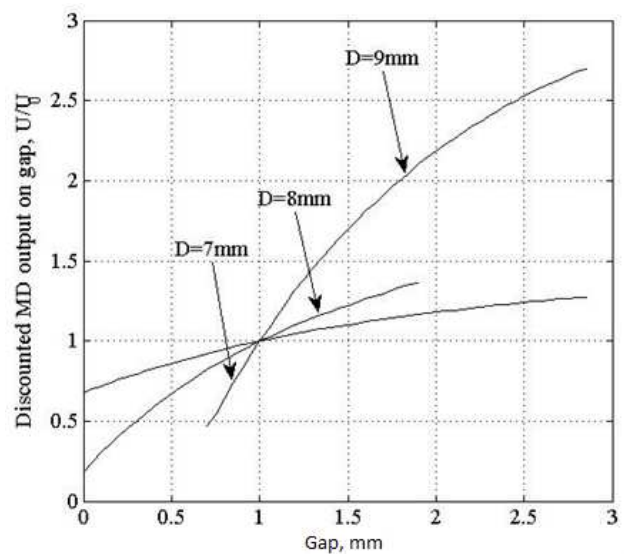


Fig. 3. MD reduced output on distance from ECP to CO dependencies (D – experimental sample diameter)

Experiments were carried out in the following steps:

1. To setup the micrometer into zero position.
2. To fix CO and locate ECP parallel to CO face in such a manner that ECP area was tightly pressed to CO face. It provides “ECP – CO” system alignment and concentricity.
3. To setup ECP on the given distance from ECP to CO with the help of a micrometer.
4. To turn on MD.
5. To move ECP to CO with the help of micrometer, recording MD output in every ECP position relative to CO.
6. To repeat items 3, 5 n times.
7. To carry out experimental data statistic processing and to build MD output on distance from ECP to CO dependency curve reducing it to MD output in the given ECP to CO position, for example, to 1 mm.
8. To carry out items 1-7 for several COs with different diameters.

The MD reduced outputs on distance from ECP to CO in the range of 0...2.85 mm is depicted on fig. 3. From fig. 3 it can be noted that with the CO diameter reducing, the curve steepness of the MD output on the distance from ECP to CO is also reduces.

Fig. 4 reflects the standard uncertainty [9] with measurement results of MD outputs from ECP to CO distance in range of 0...2.85 mm. It can be noted that standard uncertainty is decreased with increasing distance from ECP to CO. It can be explained by higher ECP sensitivity to “ECP – CO” system angular displacement and misalignment on small distances from ECP to CO.

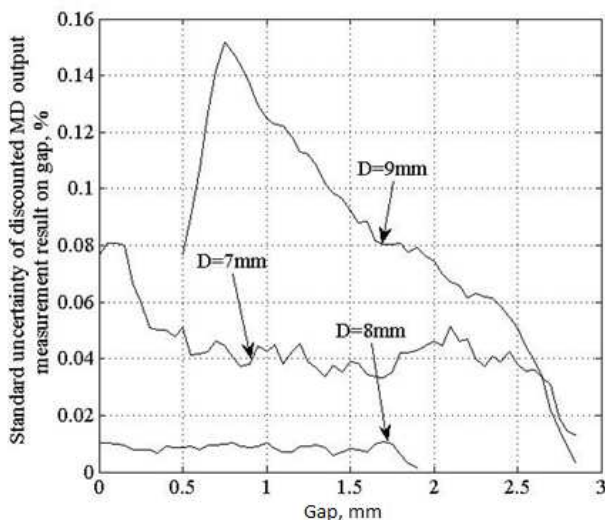


Fig. 4. MD reduced output standard uncertainty on distance from ECP to CO dependency

With experimental sample diameter influencing MD output on distance from ECP to CO, the dependence curve nonlinearity (fig. 3) was defined by experimental data linear approximation and its error definition is expressed in percentage, as:

$$\varepsilon = \frac{U_e - U_a}{U_e} 100,$$

where  $U_e$ ,  $U_a$  are MD output experimental and linear approximated data.

Fig. 5 shows linear approximation error on distance from ECP to CO in distance range of 0.75...1.25 mm. It can be seen from fig. 5 that a smaller CO diameter causes the reduction of the MD output curve dependency nonlinearity on the distance from ECP to CO.

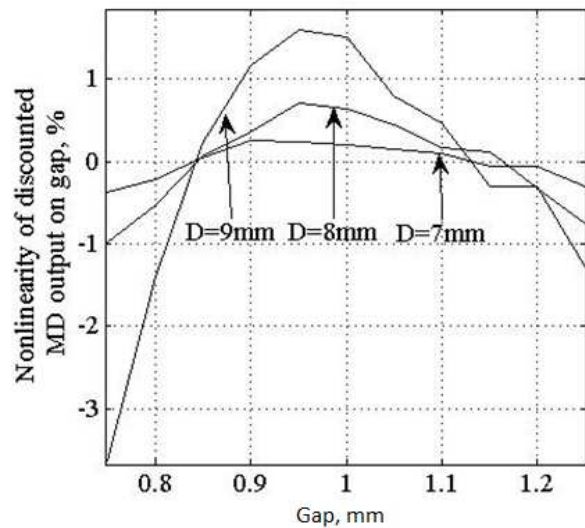


Fig. 5. MD reduced output nonlinearity

With the purpose to verify “ECP – CO” system mathematical model, that is, ECP inductance on CO diameter and ECP source current frequency dependencies when the distance from ECP to CO is constant, experimental samples are being prepared. The experimental samples must have identical conductivity and relative permeability. The MD also needs further improvement.

### Conclusions

As it can be seen from the results of the experiments the ECP reduced inductance on distance from ECP to CO depending on the CO diameter that has been validated by the “ECP – CO” system mathematical model presented in [3]. It confirms the fact, that with smaller CO diameter the ECP inductance is reduced on the distance from ECP to CO, thus reducing the curve dependence nonlinearity and its steepness.

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