Analysis of the Impact of Major Influencing Factors on the Waveform of the Surface Eddy Current Probe for Electroconductive Nonmagnetic Pipe Thickness

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Abstract. The results of computer simulation of interaction between the magnetic field of the surface eddy current probe and a conductive pipe performed in COMSOL Multiphysics were used to determine the dependences of the probe on major influencing factors: pipe wall thickness, the gap between the probe and the pipe surface, material electroconductivity, the pipe wall curvature, areas with a smooth V-shaped change in the thickness and local thinning of a spherical shape, misalignment of the probe axis relative to the pipe surface and transverse displacement of the probe axis.

1. Introduction

Surface eddy current probes (SECP) are widely used to solve various problems of non-destructive testing: measuring the thickness of electroconductive objects and non-conductive coatings on metal surfaces, control of metal and alloy electroconductivity, inspection of products of different shapes, structuroscopy of parts of non-magnetic and ferromagnetic alloys.

The advantages of the surface eddy current probe are their versatility, the ability to control objects of plane, cylindrical and complex forms with one-sided access to the test object, locality that provides high resolution and precise determination of the defect zone when scanning the surface of the test object [1,2].

One of the essential inspection problems efficiently solved via SECP is measuring the wall thickness of pipes made of electroconductive nonmagnetic material and the thickness of the dielectric coatings on these pipes or the air gap between the probe and the pipe surface.

A practical example of SECP application is testing of the wall thickness of light-alloy drill pipes (LADPs) manufactured from duralumin D16T. The advantages of LADPs compared to steel pipes are low weight, low flow resistance and non-magnetic materials, the properties which are required for inclinometer survey.

The paper addresses the analysis of the interaction between the magnetic field of the SECP and the electroconductive pipe taking into account the main influencing factors to measure the wall thickness of the pipe and the gap between the SECP and the pipe surface.

2. Problem formulation

Figure 1 schematically shows the structure of the transformer SECP commonly used to inspect the wall thickness. The SECP comprises excitation coil w_1, measuring coil w_{21} and compensating coil w_{22}. With no test object present, their initial EMFs cancel each other out due to subtractive polarity of the measuring and compensation coils. If the electroconductive test object is located near the SECP, a waveform caused by the eddy current in the object arises at the probe output. In the general case, the amplitude and phase (complex components) of the induced EMF are determined by the amplitude and frequency of the excitation current, SECP design parameters, electromagnetic characteristics of the material and geometric parameters of the test object, and the relative position of the SECP and the test object.

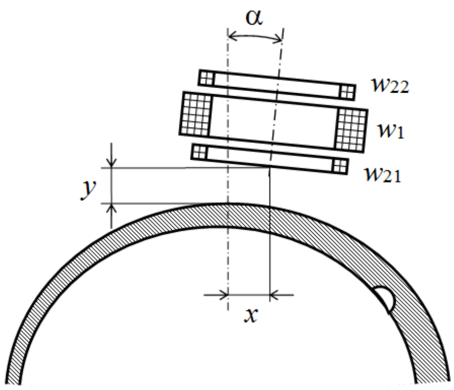

Figure 1. SECP interacting with the conductive pipe.

To calculate the results of the interaction between the SECP magnetic field and the electroconductive test object and to find the function of the influencing parameter conversion into the SECP waveform parameters, we can use the analytical models well proven to investigate different variants of interaction with a sufficiently high degree of compliance with theoretical and experimental results [1,3,4].

However, these analytical results have been obtained for a limited class of interactions typically involving axisymmetrical relative positioning of the probe and the test object of a regular geometric shape (plane, spherical, cylindrical, etc.). Therefore, the analytical results do not allow us to study the effect of different factors such as linear and angular displacement of the transducer symmetry axis with respect to the test object symmetry axis, irregular shape of the test object, local defects such as cracks or local thinning, the proximity of the test object edge on the SECP signal.

Numerical simulation methods are free of this drawback and the finite element method (FEM) is supposed to be the most appropriate for the considered class of problems. FEM is a numerical method for solving differential equations with partial derivatives and integral equations derived when solving the problems of applied physics. This method is widely used to solve the problems of solid mechanics, heat transfer, hydrodynamics and electrodynamics. FEM provides an example of versatility of the real problem solution, an object of any form can be treated, approximation of standard geometric shapes is not required, asymmetric problems taking into account the heterogeneity parameters of materials and environments can be solved [2].

FEM accuracy is mainly determined by the density of the mesh applied. Computational capabilities of modern computers allow processing of a large amount of data. In addition, a lower density mesh can be made in the areas with small values of the electromagnetic field gradient. Thus, FEM can provide high precision simulation with no significant restrictions on the complexity of the boundary conditions [5].

With regard to the problem of interaction between the SECP magnetic field and the conductive pipe, FEM allows the analysis of the effect of not only material conductivity σ, wall thickness T and the pipe outer diameter D, the gap between the SECP and the pipe surface y on the SECP output signal, but in contrast to the mentioned analytical models, it enables the analysis of the effect of linear x and angular α misalignment of the SECP and the pipe, non-uniform thickness and the presence of pipe wall local thinning (figure 1).

The SECP parameters set in the simulation were as follows (figure 1): the outer diameter of the excitation coil was 40 mm; the inner diameter of the excitation coil was 32 mm; the height of the excitation coil was 10 mm; the diameter of the middle turn of the measuring and compensation coils was 30 mm; the distance between the planes of the middle turns of the measuring and compensating coils spaced symmetrically relative to the excitation coil was 16 mm. The frequency of the excitation current was assumed to be 100 Hz.

The test object was a nonmagnetic pipe with a specific electric conductivity σ in the range of (10...25) MS/m, with a nominal outer diameter D = 147 mm and wall thickness T in the range of (5...15) mm. The distance between the SECP measuring coil and the pipe surface varied in the range of (3...15) mm.

3. Simulation of the interaction of the secp magnetic field and the test object using comsol multiphysics software

3D model was created using COMSOL Multiphysics, version 4.3a. When applying the mesh, the parameters of which directly affect the calculation accuracy, a higher density mesh was used for regions with a higher gradient of the change in the magnetic field (figure 2).

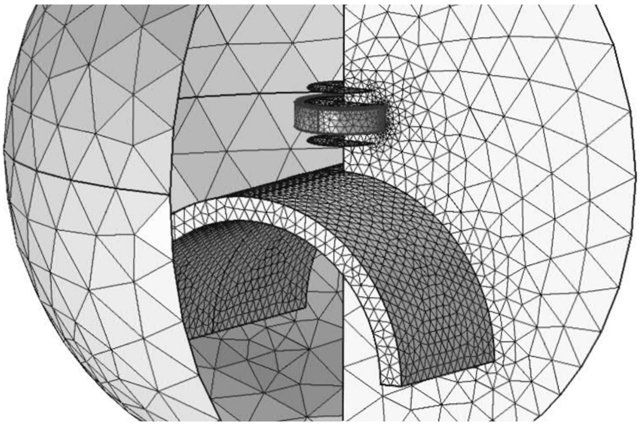

Figure 2. Mesh applied to the model in COMSOL.

To test the adequacy of the developed model, the results of computer and physical modeling of SECP interaction (Figure 1) with a duralumin pipe were compared. The outer diameter of the pipe was 147 mm and electroconductivity was σ = 16 MS/m. The results of computer simulation differ from those obtained in physical simulation by not more than 3% in the above range of the influencing parameters for pipe thickness *T* and air gap *y*. It indicates their high adequacy.

Figure 3 shows the hodographs of the relative induced SECP voltage for the change in the pipe wall thickness *T*, the gap *y* and the material conductivity σ obtained by numerical simulation for other values of the influencing parameters. These results qualitatively coincide with the results obtained using the analytical model [1]. The quantitative difference in the tested range of changes in the influencing parameters does not exceed 7%. These findings are generally consistent with the results obtained in [5].

Figure 4 shows the results obtained in numerical modeling of the effect of the test object surface curvature on the SECP signal. The dotted line shows the hodograph for the change in the gap *y* for a plane surface. The solid lines indicate the hodograph of the curvature radius *R* in the range (50...∞) mm and (-∞...-73) mm. Positive radius values correspond to the radius of the convex surface (outer pipe surface), and negative radius values indicate the concave surface (inner pipe surface). The analysis of the dependencies plotted in Figure 5 shows that the hodographs of the change in the test object surface curvature are close to a straight line intersecting the hodograph of the change in the gap at an angle of 5...10°.

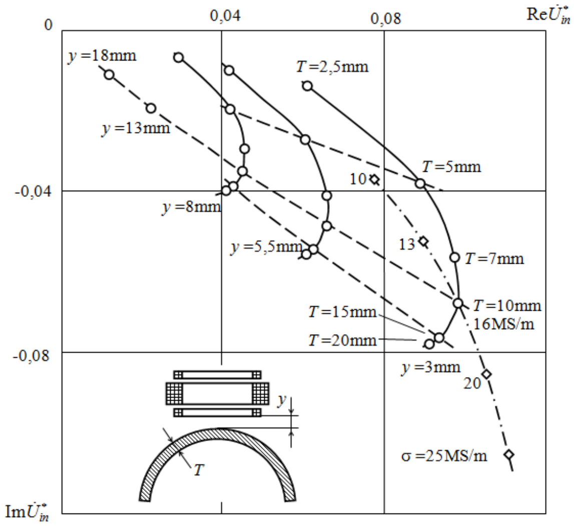

Figure 3. Hodographs of the relative induced SECP voltage for the change in the pipe wall thickness T, the gap y and the material conductivity σ.

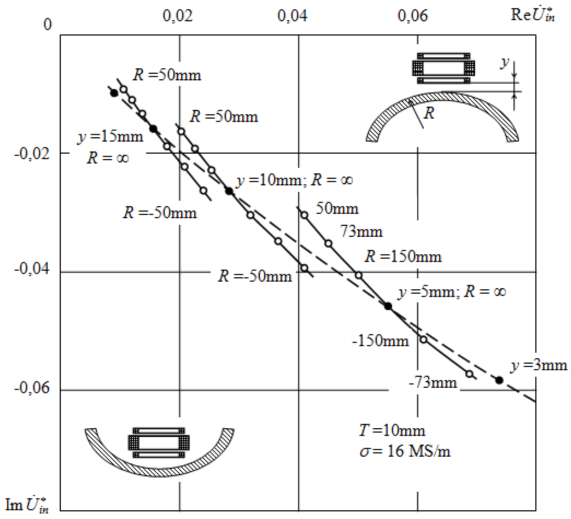

Figure 4. Hodographs of the relative induced SECP voltage for the change in the gap and the radius of the test object surface curvature.

Figure 5 shows the numerical results for the effect of the displacement x along the SECP longitudinal axis on the SECP waveform relative to the transverse pipe axis. Dashed lines show the hodographs of the change in x for three values of the pipe thickness T, and solid lines indicate the hodographs of the change in the gap y for the same thicknesses. The analysis of the modeling results shows that the hodographs for displacement x are close to a straight line almost coinciding with the hodographs for the change in the gap y. A significant change in the SECP waveform caused by displacement is found at x exceeding the half radius of the SECP coil turns.

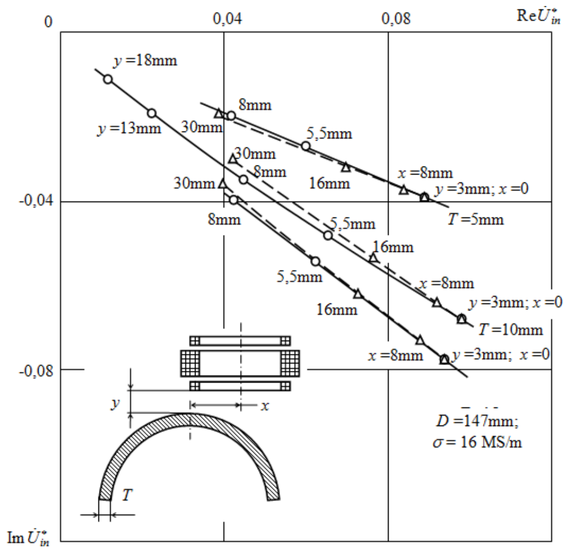

Figure 5. Hodographs of the relative induced SECP voltage for the longitudinal axis with respect to the pipe transverse axis.

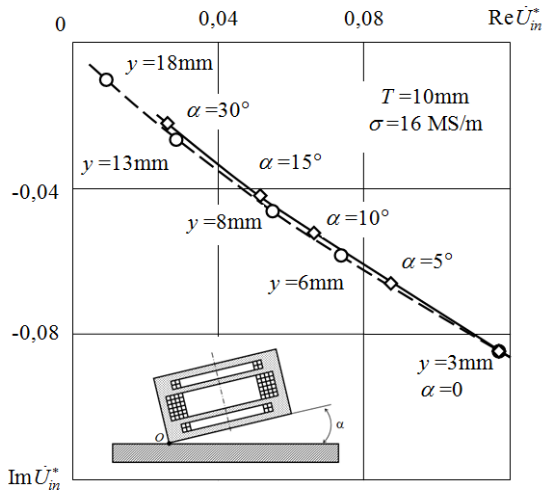

Figure 6. Hodographs of the SECP relative induced voltage for the change in the skew angle α.

Figure 6 shows the results obtained in numerical modeling of the effect of the angle α between the SECP butt end and the test object on the ECP signal. The test object was a conductive plate. It was assumed that the SECP is skewed relative to the common point O between the plate surface and the edge of the SECP body with a diameter of 44 mm and a height of 22 mm. The hodograph $\Delta\dot{U}_{in}^{*}$ for the change in the skew angle α (dashed line) is almost equal to that for the change in the gap y. For the considered SECP sizes, it can be assumed that the change in the induced voltage amplitude caused by the skewness of 5° is similar to the change in the gap y from 3mm to 5 mm.

In pipe operation, LADP in particular, the pipe wall wears unevenly due to mechanical and corrosive attack. In this regard, we studied the effect of V-shaped and local changes in the wall thickness on the SECP waveform.

The hodograph of the induced SECP voltage with respect to the change in the thickness of the V-shaped object in the normal cross section virtually coincide with the hodograph for the change in the thickness of the plane object. Hence, the signal of the SECP located above the object under this thickness variation and the value of the wall thickness T_0 along the SECP longitudinal axis corresponds to the SECP signal located above the plane object with a wall thickness of T_0.

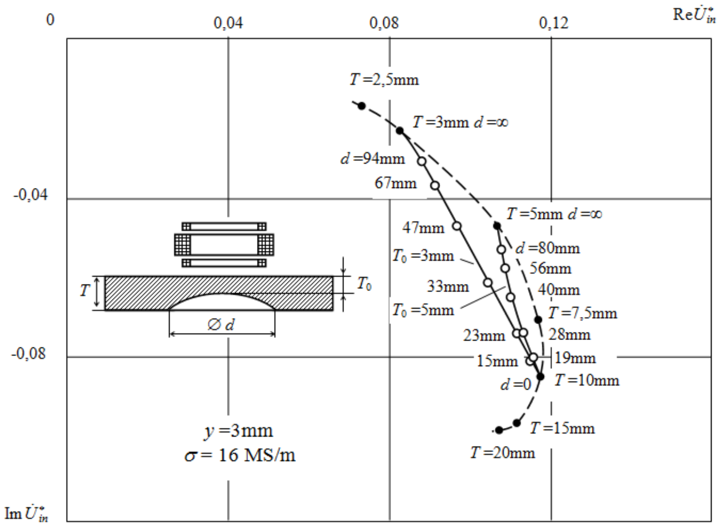

Figure 7. Hodographs of the SECP relative voltage for the change in the diameter of the spherically-shaped local thinning.

Figure 7 shows the results obtained in numerical modeling of the effect of local thinning on the SECP signal. In this case, similar to the previous one, the test object was a conductive plate taken for greater clarity. The local thinning was assumed to be of a spherical shape located on the inner surface of the plate. The depth dimensions were set by the two parameters: the minimum depth from of the outer surface T_0 and the circle diameter d on the inner surface. The analysis of the results shows that the hodographs of the induced voltage for the change in the thinning diameter d in the range from 0 to ∞ (solid lines) are close to straight lines connecting the points in the hodograph for the change in the plate thickness (dotted line) corresponding to thicknesses T and T_0. A sharp change in the SECP signal due to local thinning can be observed at d values commensurable with D_0 values.

4. Conclusion

Methods of numerical modeling, the finite element method in particular, are effective techniques to simulate the interaction of the SECP with an electroconductive test object in case the test object and the SECP coil are of a complex shape or the arrangement of the probe relative to the object is asymmetrical. A high degree of adequacy of the results obtained in computer simulation and physical simulation of this interaction in COMSOL Multiphysics is exemplified by numerical modeling of the SECP – electroconductive pipe interaction with respect to the problem of pipe wall thickness measuring. The performed analysis considers the effect of the major influencing factors on the SECP signal: pipe wall thickness, the gap between the probe and the pipe surface, material conductivity, pipe wall curvature, the presence of the areas with smooth V-shaped change in the wall thickness and local thinning of a spherical shape, skewness of the probe axis relative to the pipe surface, lateral misalignment of the probe axis.

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