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NUMERICAL SIMULATION OF NON-DESTRUCTIVE REMOTE FIELD EDDY CURRENT TESTING OF ROLLED METAL TUBES

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Abstract

The first publications describing the physical principles of the non-destructive remote field eddy current testing method appeared about 30 years ago. This method allows to significantly expand the field of application of eddy current testing. However, due to the lack of a theoretical justification, this method did not get widespread use around the world. Domestic publications in this area are completely absent, and the descriptions given in few foreign publications often contradict each other. There are no results of full-scale simulation using numerical methods in available domestic and foreign sources. The distinctive feature of this method under consideration is the ability of detecting defects on the external (with respect to the eddy current transducer) side of the tested object, which is impossible for the classical eddy current method due to the limited eddy current penetration depth. The basics of the method were considered, the distinctive features were presented, and the advantages and disadvantages of remote field eddy current testing of metals were pointed out. A numerical simulation with the subsequent analysis of the obtained results has been carried out, the transducer design for remote field eddy current testing is given. The influence of various factors on the change in the added voltage of the signal coil of the eddy current transducer in the presence of a defect in the external wall of the tube was considered. Expressions that determine the optimal ratio of the diameters of the transducer and the tested product were obtained. The values of the test parameters and the limiting wall thickness of the tested ferromagnetic product were determined

Keywords

Non-destructive testing, electromagnetic testing, eddy current testing, remote field eddy current testing, tubes defectoscopy, numerical simulation

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Introduction. Electromagnetic non-destructive testing methods are widely used to achieve high quality of products made from metals and alloys. When solving the problems of steam generator tubes testing, non-destructive techniques are increasingly being used, based on the remote field eddy current method. The key factor determining the operability of steam generators (one of the most important objects under test) is the heat exchange tubes condition. The main types of their damage include defects of corrosive nature — spots that develop with corrosion cracking, pitting (point) corrosion and large shallow corrosion spots. Tube surfaces that are in direct contact with gaseous and liquid aggressive media of different composition and at different temperatures wear very intensively. The emergence of defects is primarily caused by the presence of active impurities in the medium — chlorides and sulfates, deposits of which contribute to the progress of corrosion [1, 2].

The eddy current method of non-destructive testing is based on the interaction analysis of the external electromagnetic field with the electromagnetic field of eddy currents induced by the exciting coil in the electrically conducting object under test. The density of eddy currents in the object depends on the geometrical and electromagnetic properties of the object, as well as on the relative position of the measuring eddy current transducer and the object. A harmonic or pulsed current acting in the coils of the eddy current transducer creates an electromagnetic field that excites eddy currents in the electrically conductive object. The eddy current electromagnetic field in turn acts on the transducer coils. By registering the added voltage or the change in the electrical impedance of the coil, information about the properties of the object under test is obtained [3].

One of the important features of eddy current testing is that it can be performed without direct contact between the transducer and the object. The interaction usually takes place at distances sufficient for free movement of the transducer relative to the object under test (from fractions of a millimeter to several millimeters). Therefore, eddy current testing methods produce good results even at high object movement speeds.

Also, among the advantages of the method is that the signal of the eddy current transducer is practically not affected by humidity, pressure, radioactive emissions and pollution of the gas medium or the surface of the object under test with non-conductive substances.

Eddy current methods are characterized by a shallow depth of the inspection area, determined by the penetration depth of the electromagnetic field into the tested medium. The method does not allow to perform the test for the entire thickness of the tube wall due to the strong skin effect in ferromagnetic materials [3–5].

When using the remote field eddy current testing method, the problem of analyzing the entire thickness of a ferromagnetic tube wall becomes feasible. The advantage of this method is that it has almost equal defects detection sensitivity in one-sided testing both on the tested surface and on the back surface of the ferromagnetic tube [6, 7].

The software tools “Maxwell” of the “ANSYS Electronics Desktop: Electromagnetic Suite” software package were used to create the model and perform a finite element analysis. This software is widely used throughout the world and the reliability of the results obtained in it is confirmed by extensive experience in its application for solving problems in various fields. The mathematical apparatus of “ANSYS Maxwell” software provides high-performance and accurate solutions to determine the only possible distribution of electromagnetic fields in a given computational domain under given boundary conditions.

Theoretical principles of the remote field testing method. The remote field testing method for rolled tubes involves moving the feedthrough transducer inside the tube. The transducer consists of one or several excitation coils and a signal coil located on the same axis, which coincides with the axis of the probe movement in the tube (Fig. 1). To excite a magnetic field, a sinusoidal current with a relatively low frequency is used. Induced eddy currents create their own magnetic field, which counteracts the magnetic field of the excitation coil. Due to the resistance in the tube wall and the imperfection of the inductive coupling, the magnetic field of the eddy currents does not fully counteract the primary exciting magnetic field. The geometry of the magnetic field of the eddy currents is also

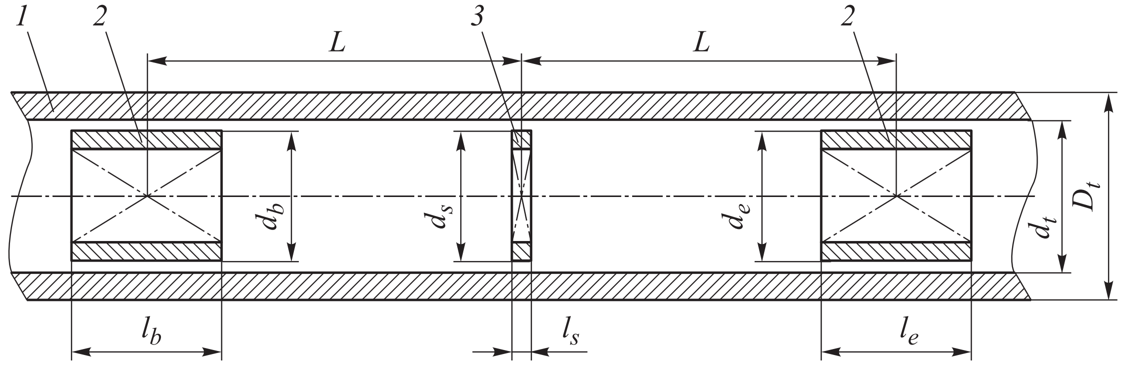


Fig. 1. General scheme of eddy current transducer for remote field testing:
1 is object under test; *2* is excitation coil; *3* is signal coil; D_t is outer diameter of the tube being tested; d_t is inner diameter of the tube being tested; d_e is diameter of the excitation coil; l_e is length of the excitation coil; d_s is diameter of the signal coil; l_s is length of the signal coil; L is distance from the center point of the excitation coil to the center point of the signal coil

different from the primary one, because the current windings have different diameter in comparison with the excitation coil winding and are located inside the object under test [5, 8, 9].

The magnetic field from eddy currents propagates more widely in the material and extends further along the tube axis. The interaction between two magnetic fields is rather complicated, but the remote field testing method uses the simple fact that the component of the total field from the excitation current is dominant close to the excitation coil, and the field of eddy currents becomes dominant at some distance from the excitation coil (Fig. 2) [7, 9, 10].

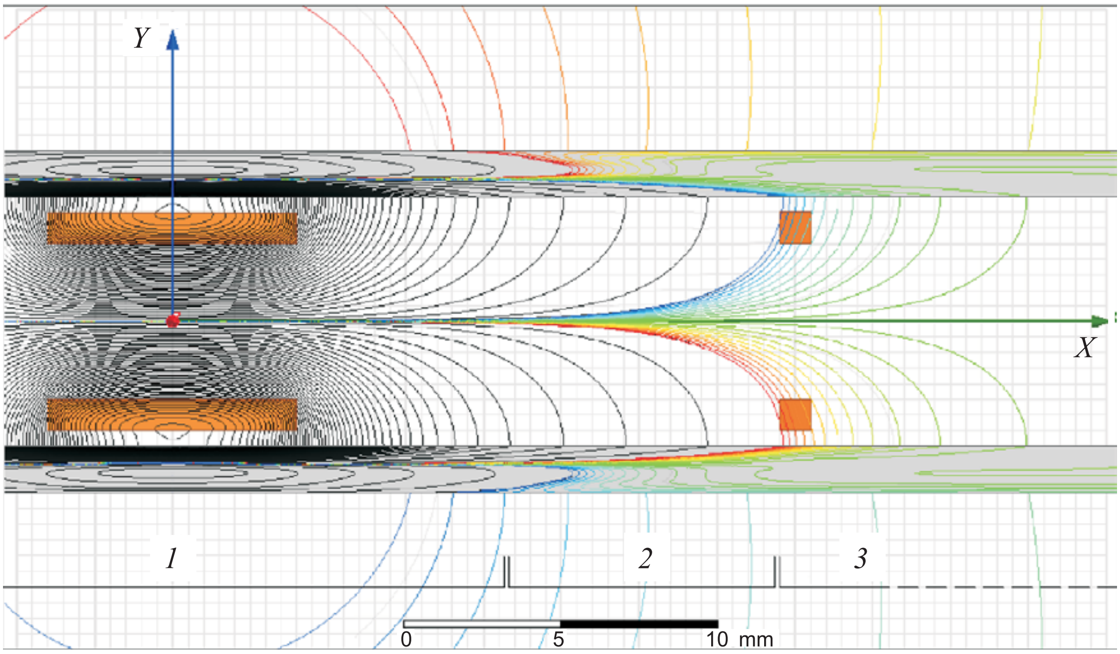


Fig. 2. The location of the field lines of the total magnetic field from the excitation current and eddy currents (for the transducer with one excitation coil):
1 is near field zone; *2* is transition zone; *3* is remote field zone

The signal (receiving) coil is placed at a distance where the total magnetic field from the eddy currents and the excitation current propagates almost in parallel to the tested surfaces. The added voltage of the signal coil is affected by all changes in the electromagnetic field in the tube body [10, 11].

The zone where a concentrated field of eddy currents is formed as a result of the interaction of the magnetic field from the excitation coil with the tube metal is called the direct field or near field. This zone cannot be used for remote field testing, since it has a rather high noise level due to an intense alternating magnetic field from the excitation coil [12].

The zone starting proximately from the direct impact zone is the transition zone. In this zone there is a significant interaction of the magnetic flux from the excitation coil and the flux caused by eddy currents. An abrupt change of the resultant field in this zone occurs due to the interaction of multidirectional fields.

In the remote field zone, the direct interaction between the excitation coil and the signal coil is insignificant. The effect occurs indirectly through the resulting total magnetic field [13].

Analysis of the eddy current transducer model for remote field testing. Conducting a series of experiments on simulation models for various wall thicknesses of the objects under test showed the dependence of the eddy currents distribution region and density on the materials properties and the given excitation frequency. Numerical models, built on the well-known dependencies of the eddy currents distribution on the exciting current frequency and the characteristics of electrically conductive materials, make it possible to determine the optimal excitation frequency.

Analyzing the simulation results, it was found that the eddy currents distribution region and penetration depth substantially depend on the excitation frequency, which is a control action and can be changed to obtain the best output signal. The penetration depth is determined by current frequency, specific electrical conductivity and magnetic permeability of the material. In the case of testing a ferromagnetic material (steel), the penetration depth is substantially limited by its magnetic permeability (skin effect). The concept of penetration depth, which is fundamental to the classical non-destructive eddy current testing method, in case of remote field testing recedes into the background compared to the eddy currents distribution region in the material of the object under test, which is characterized by section area. Thus, for remote field eddy current testing, it is necessary to select such a frequency range in which the eddy currents distribution region in the material of the object under test will be the largest one provided that the eddy currents strength is sufficient [14, 15].

For objects under test made from steel, the frequency is limited to the range of 1.5–2 kHz. With increasing frequency due to the occurrence of the surface (skin) effect, the penetration depth rapidly decreases and, therefore, the propagation zone of the eddy current remote fields decreases. With a decrease in frequency of less than 1.5 kHz, the value of the eddy currents strength decreases and, accordingly, the characteristics of the magnetic field excited by them decrease. Plots of the eddy currents distribution area (in cross section) and the eddy currents strength as a function of the selected excitation frequency are shown in Fig. 3.

The size of the alternating magnetic field excited by eddy currents is directly proportional to the size of the of eddy currents distribution region. The excitation field decreases at some distance from the coil, and the field

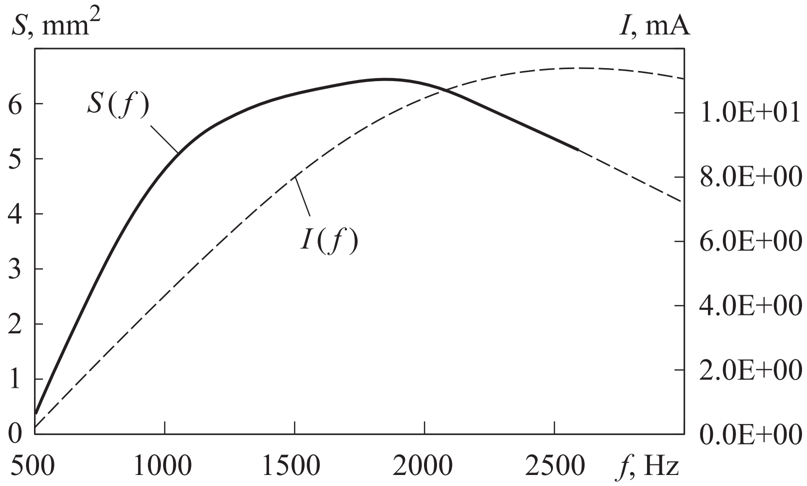


Fig. 3. The dependence of the eddy currents distribution area and strength on the exciting current frequency:

S(*f*) is plot of the eddy currents distribution area (in cross section);
I(*f*) is plot of the maximum value of the eddy currents strength

emerging from eddy currents extends further along the material of the object under test, and can be used to determine the presence of changes in the cross-sectional area of the tube being tested [5, 8, 11, 15].

Analysis of the magnetic field distribution, based on the location patterns of the field lines of the total magnetic field, shows that the maximum thickness of the tested objects made of steel during inline inspection is determined by the expression (1), since at large thicknesses the field propagating along the external surface of the product is too small to determine its changes caused by the presence of defects

$$\frac{D_t}{2} - \frac{d_t}{2} < 2 \text{ mm}. \quad (1)$$

Considering the models with objects of different sizes under test, it was found that the appropriate distance from the center of the excitation coil to the location of the signal coil is determined by the expression (2). The magnetic fields distribution pattern is presented in Fig. 4

$$L = (2...2.5)\, d_t. \quad (2)$$

Within the scope of the carried out numerical studies, the propagation pattern of the electromagnetic field in the remote region was formed and the weak field distribution in the body of the ferromagnetic object under test in the defect zone was presented (Fig. 5 and Fig. 6).

Analysis of the research results showed that the remote field eddy current testing method is sensitive to changes in the wall thickness of the product under

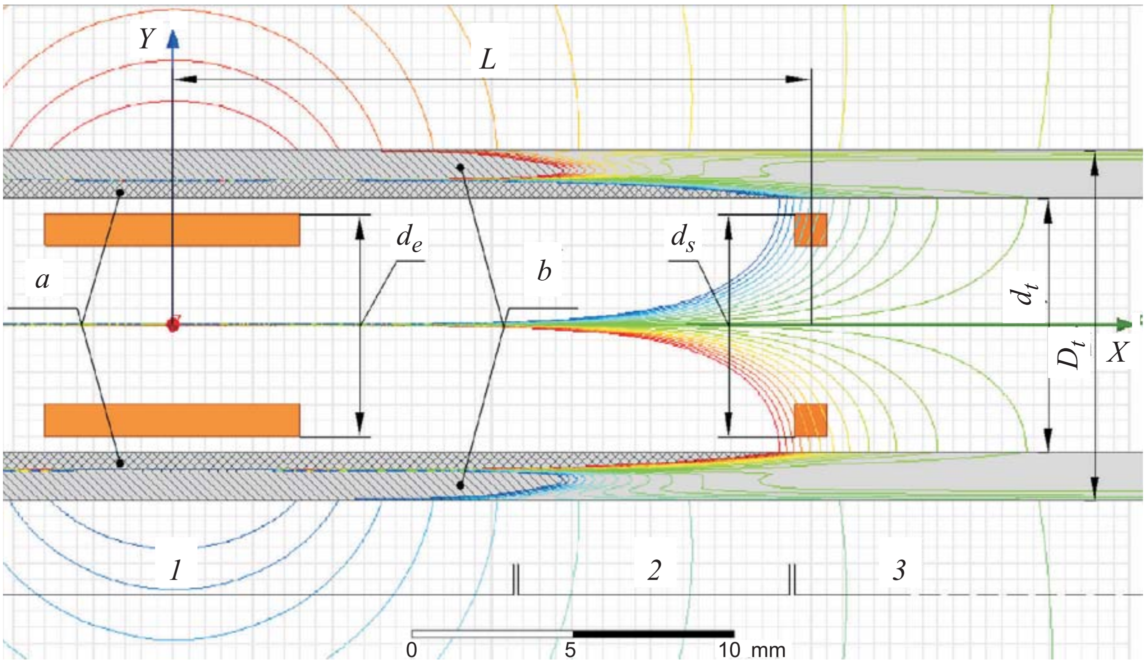
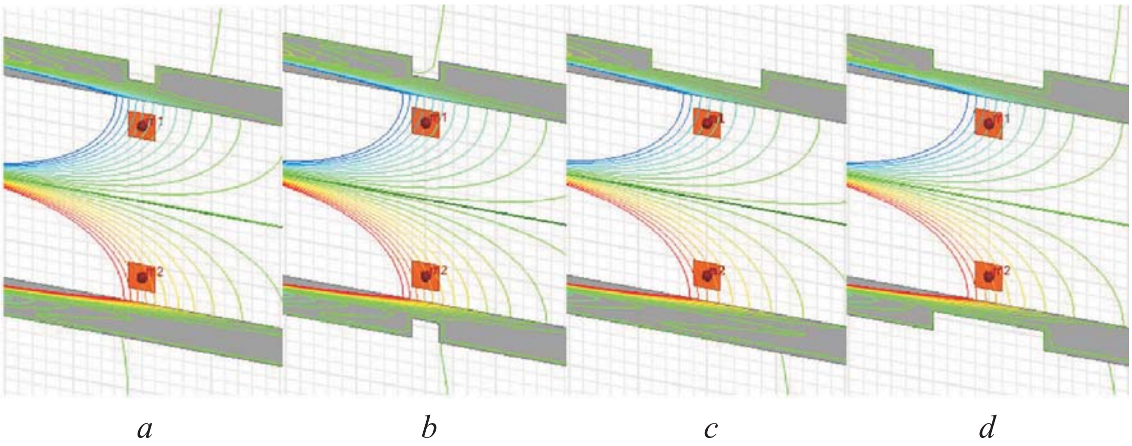


Fig. 4. The location of the field lines of the total magnetic field from the excitation current and eddy currents:

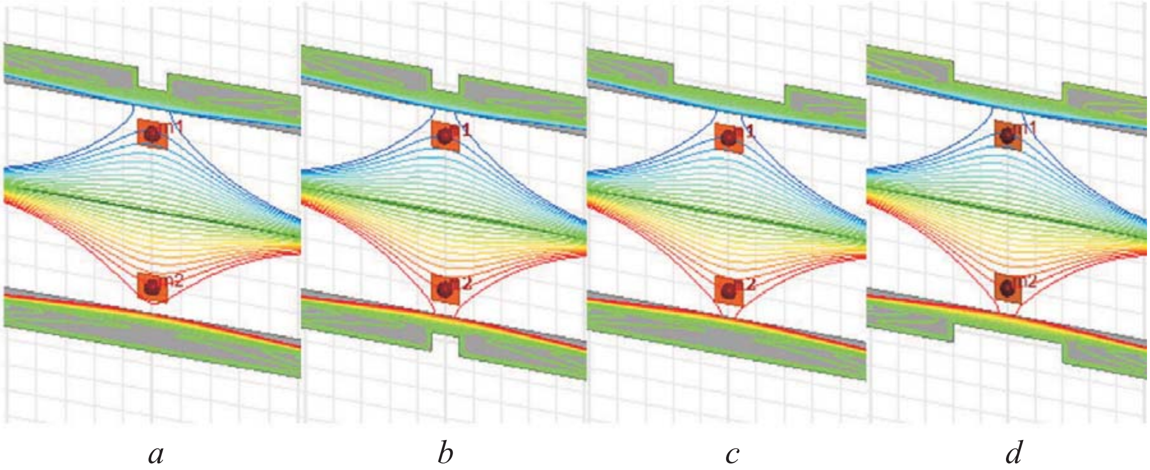
1 is near field zone; *2* is transition zone; *3* is remote field zone; *a* is region of the magnetic field created by the excitation current; *b* is region of the magnetic field excited by eddy currents in the material of the object under test; $L = 2.5d_t$ is distance from the center point of the excitation coil to the center point of the signal coil



a *b* *c* *d*

Fig. 5. The location of the field lines of the eddy currents remote fields in the defect zone for the transducer with one excitation coil (*OXY* is section of the three-dimensional model); *a* is flat-bottomed cylindrical defect, or narrow transverse defect — flat; *b* is narrow annular defect; *c* is longitudinal defect — mark, or wide transverse defect — flat; *d* is wide annular defect

test during inline inspection, however, it is only the detecting one. The emergence and growth of a defect causes changes in the added voltage, but based on these changes it is difficult to judge about the types of defects causing them.



a *b* *c* *d*

Fig. 6. The location of the field lines of the eddy currents remote fields in the defect zone for the transducer with two excitation coils (*OXY*, *a*–*d* see Fig. 5)

There are very small differences, it is definitely possible to recognize only discontinuities with a small volume when comparing them with large defects. According to the results of numerical simulation, the nature of the influence of various factors on the change in the added voltage of the signal coil in the presence of a defect was determined, the generalized pattern of which is shown in Fig. 7.

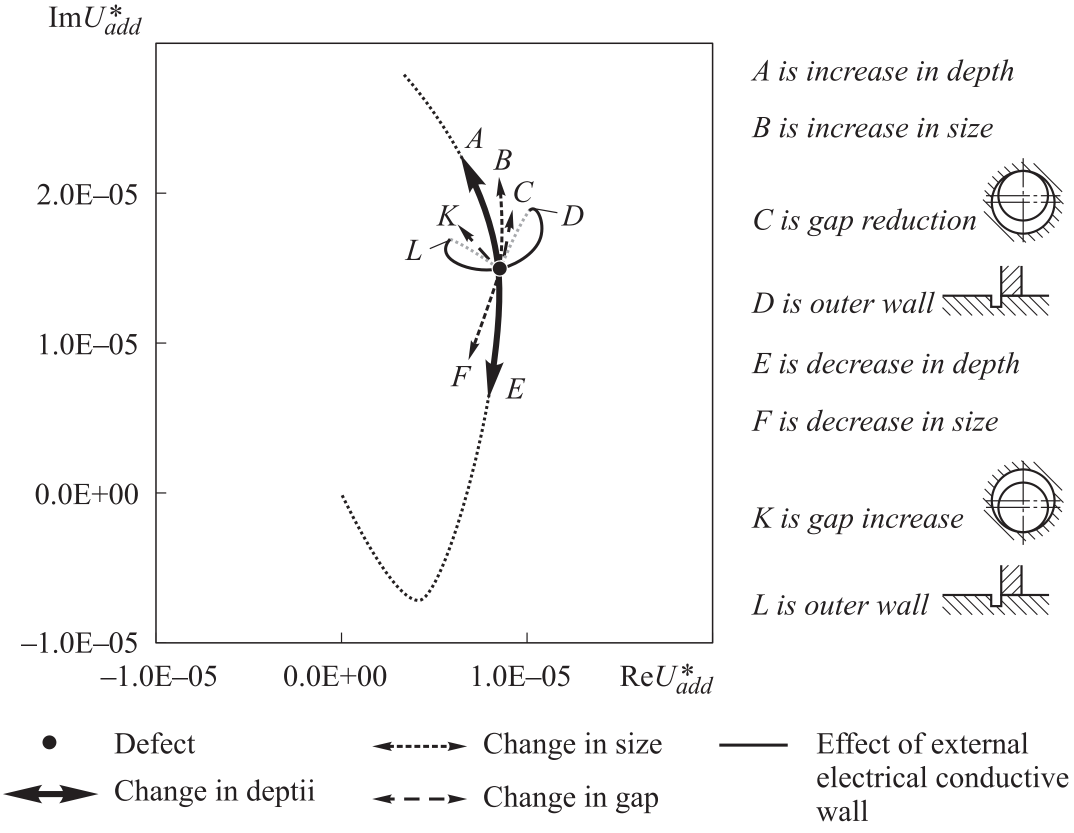


Fig. 7. The influence of various factors on the change in the added voltage of the signal coil in the presence of a defect

Conclusion. Remote field eddy current testing is a viable and effective addition to the traditional testing technique in near fields of eddy currents. The method allows testing of rolled metal tubes with almost equal sensitivity of detecting defects on the inner and outer walls of the object under test, however, it should be noted that the sensitivity to defects will be less than that of the classical eddy current method, therefore, in practice, it is better to use a combined transducer for test in near and remote fields.

Equipment for non-destructive remote field testing is susceptible to the slightest changes in the wall thickness of the tube being tested. The design simplicity and the possibility of non-contact testing provide powerful capabilities for carrying out automated test with a high degree of reliability. Despite the advantages of the method, this area of non-destructive testing was poorly developed by domestic designers. Taking into account modern economic and foreign policy conditions, as well as the adopted course on import substitution, the development of the theory and design of domestic devices based on the remote field test method becomes relevant.

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REFERENCES

[1] Efimov A.G. By the influence of corrosion products and metal deposits on the detection of defects in the continuity of the electromagnetic control of steel products. Part 1. *Kontrol'. Diagnostika* [Testing. Diagnostics], 2012, no. 1, pp. 26–33 (in Russ.).

[2] Efimov A.G. By the influence of corrosion products and metal deposits on the detection of defects in the continuity of the electromagnetic control of steel products. Part 2. *Kontrol'. Diagnostika* [Testing. Diagnostics], 2012, no. 2, pp. 25–33 (in Russ.).

[3] Efimov A.G., Shubochkin A.E., Mart'yanov E.V. Modern eddy current flaw detection system for rolled steel. *Kontrol'. Diagnostika* [Testing. Diagnostics], 2014, no. 12, pp. 19–20 (in Russ.).

[4] Shubochkin A.E. Razvitie i sovremennoe sostoyanie vikhretokovogo metoda nerazrushayushchego kontrolya [Development and current state of eddy current method of nondestructive control]. Moscow, Spektr Publ., 2014.

[5] Efimov A.G., Fedosenko Yu.K., Shkatov P.N. Vikhretokovyy kontrol' [Eddy current control]. Moscow, Spektr Publ., 2011.

[6] Klyuev V.V., Kuzelev N.R., Artem'yev B.V., et al. Intelligent systems NDT and technical diagnostics — the basis of the safe operation of nuclear power plants. *Kontrol'. Diagnostika* [Testing. Diagnostics], 2013, no. 1, pp. 35–39 (in Russ.).

[7] Yang B., Li X. Pulsed remote eddy current field array technique for nondestructive inspection of ferromagnetic tube. *NDT&E*, 2010, vol. 25, no. 1, pp. 3–12.
DOI: 10.1080/10589750802613347

[8] Russell D., Shen V. Increased use of remote field technology for in-line inspection of pipelines proves the value of the technology for this application. *World Conf. Non-destructive Testing*. Available at: https://www.ndt.net/article/wcndt2008/papers/466.pdf

[9] Noriyasu K., Souichi U., Satoshi N., et al. Remote field eddy current testing for steam generator inspection of fast reactor. *Nucl. Eng. Des.*, 2011, vol. 241, no. 12, pp. 643–648. DOI: 10.1016/j.nucengdes.2011.03.054

[10] Procházka M. In-service inspection of heat-exchanger tubes by means of electromagnetic methods. *Defektoskopie*, 2011, pp. 127–142.

[11] Vajpayee A. Automated condition assessment of boiler water wall tubes. *SAINT-2018*. Available at: https://www.ndt.net/search/docs.php3?showForm=off&id=22348

[12] Xu X., Liu M., Zhang Zh., et al. A novel high sensitivity sensor for remote field eddy current non-destructive testing based on orthogonal magnetic field. *Sensors*, 2014, vol. 14, no. 12, pp. 99–115. DOI: 10.3390/s141224098

[13] Luo Q., Shi Y., Wang Z., et al. A study of applying pulsed remote field eddy current in ferromagnetic pipes testing. *Sensors*, 2017, vol. 17, no. 5, pp. 2–8.
DOI: 10.3390/s17051038

[14] Falque R., Vidal-Calleja T., Dissanayake G., et al. From the skin-depth equation to the inverse RFEC sensor model. *ICARCV, 2016*. DOI: 10.1109/ICARCV.2016.7838633

[15] Falque R., Vidal-Calleja T., Dissanayake G., et al. Remote field eddy current signal deconvolution and towards inverse modeling.
Available at: http://export.arxiv.org/pdf/1708.05710 (accessed: 14.05.2019).

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