Measurement system for studying steel-dielectric junctures by means of superminiature eddy-current probes

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Abstract. A superminiature eddy current probe of a transformer type designed for the study of ferromagnetic materials is developed. The developed probe operates under the control of software and hardware complex, providing a signal to the exciting coil and receiving a signal from the measuring coil. The system is designed for automatic movement of the probe at a given speed over the object of control. The data of steel-dielectric-steel object scanning are presented. Measurements were carried out linearly and discretely. The data of the influence of the gap between the measuring coil of the eddy current probe and the object of control are also presented.

1. Introduction
A qualitative and reliable assessment of the technical condition of hazardous production facilities is an important task. As a part of modern control methods, such an assessment is made on the basis of probabilistic approaches and is based on data on operating modes of the facility and factors influencing on it (stress, deformation, temperature). However, structural and surface changes occurring in product metal are generally not taken into account [1, 2]. However, it is known [3] that during the operation of a metal product, changes occur both in the volume of the metal and on its surface. Based on this, the control of metal products must be assessed using methods and instruments that provide reliable recording of surface properties.

Electrical steel is used to produce various electrical products. For example, electromagnets and elements of electric engines, generators and transformers, chokes, relays, stabilizers. Considering the fields of application of these steels, quality control of products made of such materials is a crucial task. Magnetic properties of steels are necessary for the development of effective methods of control and diagnosis of their physicomechanical characteristics, largely determining the reliability, service life and residual life of crucial components, parts, products in various industries. The paper [4] shows the successful use of hysteresis loop parameters to control physicomechanical properties of ferromagnetic steels, such as coercive force (Hc), remanent induction (Br), saturation induction (Bs), magnetic permeability (μ), and hysteresis loop area (P). The use of these parameters makes it possible to study the deep layers of parts made of ferromagnetic steels, which is important, for example, when quenching large-size products, in particular, rails or shafts for turbines of power plants, where the use of traditional destructive testing methods is unacceptable. The simultaneous study of the surface layer and deep layers can give a more comprehensive picture of the physical properties of the metal. It is possible under the condition of application of the method of magnetic noise (MN) and magneto-acoustic noise (MAN) of magnetization [5].
MN and MAN carry different information about the physical and mechanical properties of steels, and the parameters of their signals can be used to build new algorithms for monitoring and diagnostics, for example, the stress state of crucial products made of ferromagnetic steels [5, 6].

The possibility of using magnetic methods to determine the characteristics of steel is shown in a number of works performed on traditional pipe steels, such as ST2, ST4, 17g1s [7, 8].

An eddy current method is also an effective way of studying physicomechanical characteristics of steel. Eddy current method is a widely used non-destructive testing method based on the analysis of the interaction of an external electromagnetic field with eddy currents caused by it [9-16].

The complexity of the use of eddy current control methods in the study of this material is a significant increase in the magnetic field by the studied sample.

The technique of assessment and forecasting of probability of brittle destruction of the metal equipment made of low-alloy steel 09G2S with application of an electromagnetic method of control is offered [12, 13]. The method is based on the analysis of the transition functions of the "electromagnetic transducer is a metal" system resulting in the implementation of the cryogenic tensile testing to simulate brittle destruction.

The results of this work show that the electromagnetic properties of the metal change depending on different types of exposure. These studies were conducted on round samples with the use of a sensor of transmission type. However, in order to measure electromagnetic characteristics on the material of real equipment, it is necessary to use overhead probes. In this regard, the design of a proper eddy current probe (ECP) was proposed in the paper [17] and the optimal input parameters for measuring the electromagnetic response of the metal were determined.

The aim of the study was to develop, research, optimize and test the developed ECP and obtain mathematical dependencies describing the change in signal value at ECP when various properties of studied steels and transducer parameters change.

2. Materials and methods
For the purpose to measure the voltage of ECP at the dielectric-steel interface, a measuring system based on ECP [18, 19] and a digital displacement transducer (DDT) were used.

Eddy current transducer is made in the form of a transformer (Figure 1), which includes three coils: measuring, exciting and stabilizing. Also, the probe includes a magnetic circuit made of ferrite. The magnetic circuit is placed inside the platform in the form of a cylinder. The coils are wound on the outside of the cylinder and imbued with the compound. Impregnation is carried out at a temperature of 200°C and is necessary to strengthen the coils. After impregnation, a ferrite screen is placed on the platform, which increases the localization of the magnetic flux at the object of control. After placing the screen, the platform is put into a corundum washer which protects the presented structure from mechanical impacts.

During the experiment, two samples of steel (ferromagnetic) separated by a layer of paper as a dielectric were scanned. The first sample was steel 1212; the second one was steel 3414. Eddy current probe worked at frequencies in the range from 1000 to 10000 Hz. Voltage supplied to ECP measuring winding when it moved relative to the initial point of scanning was applied as a measurable parameter. The scanning was carried out continuously (ECP was moving above samples at a constant speed of 1 mm/s) and discretely (ECP was changing its position at intervals of 0.1 mm, measurement at each interval was performed for 0.5 s).
The operation of the measuring system is based on the generation and reception of a signal using a personal computer. The software controls a generator that produces a sinusoidal signal with frequency \( f_1 \) and amplitude \( U \). After generation, the signal is amplified 20 times in a special amplifier. After amplification, the signal is transmitted to the exciting coil of the ECP and generates an electromagnetic field inducing eddy currents in the object of study. In turn, the electromagnetic field of eddy currents induces electromotive force (EMF) in the measuring coils of the ECP. The EMF is a signal that allows to assess the state of the object of control. For reliable registration of the parameters of the object of control, amplification and filtering of the received signal is performed using the Delyann filter, supplemented by the second stage.

The classical scheme of the filter was supplemented by the second stage of selective amplification, designed to increase the amplitude of the signal at a given frequency. As a result of the connection of the second stage, the filtration system has a high stability and low sensitivity to a small spread of parameters of the circuit elements. After passing the filter, the signal is recorded by the software of the personal computer. The frequency of the signal on the exciting coil and the cutoff frequency are changed synchronously, which allows to provide high-quality isolation of the useful signal.

3. The study of the structure of the modified lead-tin-base bronze
In order to study the behavior of the amplitude of the ECP signal when crossing the steel-dielectric boundary, a graph was plotted to illustrate the changes in the amplitude of the signal when the sensor moved over the objects of study. The scanning area of each of the steel samples was 5 mm, the scanning area of paper – 10 mm. This method of measurement allowed to observe the ferromagnetic-dielectric boundary in relation to the movement of the sensor. The graph is shown in Figure 2.

Figure 1. Eddy-current transducer.

Figure 2. The dependence of the ECP signal on the sensor position, the scanning frequency is 1000 Hz., \( l \) – gage position, \( U \) – introduced voltage.
The two peaks on the graph correspond to the scanning areas of electrical steel samples. At the same time, the signal difference between the steel and the dielectric is clearly noticeable. In the transition from steel to dielectric, the signal first drops sharply from 6000 mV to 2000 mV. After that, the signal smoothly tends to zero. To study in details the introduced voltage changing at the ferromagnetic-dielectric interface, the digital scanning of this interface was executed and the relevant curve of introduced voltage amplitude as a function of transducer location was constructed (Figure 3). This experiment involved the local digital scanning of the objects that are under research: in this respect, the scan shots were performed at points situated at a distance of 0.1 mm from one another.

This experiment allows to draw the following conclusion: at the steel-dielectric interface, response from ferromagnetic is not suddenly drops to zero but decreases in quadratic dependence (Area 1). At that, minimum value of signal amplitude is 50 mV. Increasing of signal amplitude progressively as approaching the second steel sample occurs in dependence that is close to exponential (Area 2).

The resulting dependence is due to the residual voltage in ECP measuring windings. Closed power lines are exuded in electrical steel field. Due to this the electromagnetic field generated by eddy currents and preventing the self-inductance in measuring winding will not strongly affect on inserted voltage. Thus response value does not decrease to zero because of the influence of the ferromagnet on ECP.

The influence of a ferromagnet on ECP may be explained by the presence of steel self-magnetic field, which closes at ECP even at a relatively large distance.

In this case voltage value at measuring winding is much less than voltage applied to winding when ECP is placed directly above steel. It is seen on the diagram that voltage continues to decrease as the distance between ECP and steel increases. As we approach to the second steel sample, voltage amplitude increases. This increase occurs exponentially, which is caused by the addition of magnetic fields of the first and second samples.

To estimate the influence of ECP signal frequency on measurement results, the dependence of the amplitude of the applied voltage on the position of the sensor at a frequency of 10000 Hz was developed. The results of the experiment are shown in Figure 4.
Figure 4. The dependence of the ECP signal on the sensor position, the scanning frequency is 10000 Hz, \( l \) – gage position, \( U \) – introduced voltage.

Figure 5. The dependence of the ECP signal on the sensor position, discrete type of scanning, frequency is 10000 Hz, \( l \) – gage position, \( U \) – introduced voltage, \( S_1 \) – area 1, \( S_2 \) – area 2.

The qualitative nature of the dependence of ECP voltage on its position has practically not changed. Two peaks of the applied voltage correspond to the two samples under study. Sudden drop in voltage corresponds to area of dielectric location, that separated the samples. However, the rate of voltage drop has significantly changed when moving away from the first sample. In addition, the minimum voltage (5 mV) has changed, that corresponds to the moment when sensor was passing above dielectric. This dependence can be explained by the increased magnetic losses in steel with the growth of frequency of the eddy current probe to the value of 10000 Hz. Due to magnetic losses, the influence of the sample is significantly less than in the case of the corresponding scan frequency of 1000 Hz. When comparing Figure 5 with Figure 3, a change in the nature of the applied voltage drop is clearly noticeable. At a frequency of 10000 Hz, the input voltage drop occurs exponentially. The increase in the input voltage in the area 2 also occurs exponentially.

In the course of the final experiment, the influence of the gap between transducer and electrical steel on voltage applied to ECP measuring winding was studied. In the course of the experiment, sample No. 1 was subject to a digital scanning. Measurements were made at a current frequency of 1000 Hz, the gap increased at an interval of 0.1 mm. The results of the experiment are shown in Figure 6.
Figure 6. Dependence curve of induced voltage on gap while discrete scanning at 1000 Hz, \( l \) - object distance, \( U \) – introduced voltage.

The presented dependence shows that when the sensor was removed from the steel, voltage decreased exponentially. This is due to the inadequate depth of penetration of an electromagnetic field generated by ECP exciting winding in steel when it is placed at a large distance from the object of control. In addition, influence of magnetic lines of steel on measuring winding becomes noticeably weaker with increasing of a distance defect.

4. Conclusion
In the paper, the results of measurements of the voltage introduced into the measuring coil of the eddy current probe at the boundaries of the steel-dielectric section are presented and analyzed. To analyze the characteristics of electrical steels, functions based on characterizing the magnitude of response of the eddy current probe when changing different parameters are obtained. It allows to develop the sensor intended for measurements of characteristics of electrotechnical steel and to optimize its parameters.

The studies presented in this paper allow us to analyze the state of steel objects based on the response of the eddy current probe and prove the possibility of using the sensor to examine the structural properties of steels.

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