Three-axis orthogonal transceiver coil for eddy current sounding

D Sukhanov, K Zavyalova and M Goncharik
Tomsk State University. Tomsk, Russia

E-mail: sdy@mail.tsu.ru

Abstract. We propose the new structure of three-axis transceiver magnetic-induction coil for eddy current probing. Due to the orientation of the coils, the direct signal from the transmitting coil to the receiving coil is minimized, which provided a high dynamic range. Sensitivity in all directions is provided by combining coils of different orientations. Numerical simulation and experimental studies of such a system have been carried out and confirmed the applicability of the proposed method and the mathematical model.

1. Introduction
Eddy current flaw detection [1-7] has found wide application in modern industry, but the problem of increasing of the dynamic range [8-10] of probing systems is still topical. Variable magnetic fields have a high penetrating ability, and even in electrically conductive media it is possible to detect metal objects. In addition, alternating magnetic fields induce currents, which are very sensitive to electrical contact disturbances. This feature is used in flaw detection to control the integrity of metal structures. The disadvantages of eddy current sounding include a short range of sounding and a significant influence of the source on the receiver. In this case, the presence of a direct signal leads to a decrease in the dynamic range. To minimize the direct signal, various technologies are used. For example, short-pulse sounding, when the signal transmission is abruptly interrupted, and then a sensitive receiver is activated that captures the fields generated by the residual eddy currents in the object [1,5]. The disadvantage of this approach is the need to apply pulses with high-frequency filling, which do not penetrate through the electrically conductive barriers. Another way to increase the dynamic range is to use differential magnetic induction sensors [8, 10]. But, most differential sensors have anisotropy, and lack of sensitivity in certain directions. A new design of a three-axis coil is proposed that minimizes the direct signal from the source to the receiver and is sensitive in all directions.

2. Construction of 3-axis coil
The proposed three-axis coil consists of three independent loops located in orthogonal planes (Figure 1). The peculiarity of such a system is the fact that if one of the coils starts creating an alternating magnetic field, then in other coils this field will not create an induction current. But if an electrically conducting object appears in the vicinity of the system, it will cause perturbations of the field and these disturbances will cause induction currents in neighboring coils. Thus, a three-axis coil can be a sensitive sensor of electrically conductive objects and can allow a high dynamic range of measurements.
In fact, a three-axis coil allows you to measure three independent signals, taking into account all combinations of coils and the reciprocity theorem. The first signal is measured when the X-oriented coil is being used for transmission, and Y is the oriented coil for receiving. The second signal is measured when the X-oriented coil is being used for transmission, and Z-oriented coil for receiving. The third signal is measured when the Z-oriented coil is being used for transmission, and Y-oriented coil for receiving. As a result, it turns out that the Z-oriented coil should be able to work both for reception and transmission. Technically this requires the complexity of the multiplexing scheme, so it is suggested to make two Z-oriented coils, one will be the transmitting coil, and the other will be the receiving coil.

3. Computation of apparatus function of the system based on 3-axis coil
The field of a single coil is calculated on the basis of the Biot-Savart-Laplace law. Let us imagine the reaction of the system on electrically conductive objects in space in the form of a scalar product of magnetic field inductions of the transmitting and receiving coils. Consider square coils with side lengths of 6 cm, the center of all coils is at the point (0, 0, 0) of the coordinate system. The field was observed in the z = 5 cm plane. Figure 2a shows the product of the magnetic fields of the X-oriented coil and the Y-oriented coil. It can be seen that the sensitivity region of the system of these coils has a four-petalled appearance. Moreover, in the center and along the X and Y axes, this system is not sensitive to the presence of heterogeneities. In Figure 2b the scalar product of the fields of X-oriented coil and the Z-oriented coil is shown. The reaction on heterogeneity has a two-petalled appearance. This coil system is not sensitive to the heterogeneities lying on the Y axis. Figure 2c shows the scalar product of the fields of Y-oriented coil and the Z-oriented coil. The reaction to heterogeneity also has a two-petalled appearance. The Y- and Z-coil system is not sensitive to the heterogeneities lying on the X axis.
To calculate the response of a system to an arbitrary object it is sufficient to perform a convolution of the response to a point object and a function describing the shape of the object. Thus, the result of scanning measurements using X-oriented and Y-oriented coils can be written as:

\[ U_{XY}(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} M(x', y') A_{XY}(x-x', y-y') dx' dy', \quad (1) \]

where \( M(x', y') \) - function describing the form of an object (0 – no object, 1 – object is present), \( A_{XY}(x, y) \) - scalar product of magnetic induction vectors of X-oriented and Y-oriented coils.

Similarly for other combinations of source and receiver coils:

\[ U_{XZ}(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} M(x', y') A_{XZ}(x-x', y-y') dx' dy', \quad (2) \]

\[ U_{YZ}(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} M(x', y') A_{YZ}(x-x', y-y') dx' dy', \quad (3) \]

In figure 4a shows a simulated test object. In figure 3 shown the result of the signal simulation during measurements between orthogonally oriented coils with help of formulas (1-3).
Figure 4. The specified (a) form of the test object and the restoration of its contour (b) by the formula

$$\sqrt{|U_{XY}|^2 + |U_{XZ}|^2 + |U_{YZ}|^2}$$

As a result of numerical simulation, it can be concluded that it is possible to visualize the contour image of an object from the measurements of a three-axis coil.

4. Experimental tests

For experimental studies, an experimental setup based on a three-axis coil, a two-axis scanner, and a personal computer with a sound card was developed.

As shown in Figure 1 there are two Z oriented coils, one of which is connected to the ADC, and the other to the DAC. This connection allows you to measure all combinations of signals from one coil to another and also measure the reference signal for synchronizing the source and receiver. In total, 4 combinations of signals can be measured. When one DAC channel is operating, two ADC signals are measured, and when the second DAC channel is operating, the other two signals at the input of the two-channel ADC are measured. As a DAC, the output of a sound card is used, and as an ADC - the input of a sound card.

In Figure 5 provides an explanation of the type of signals passing from the DAC and coming to the ADC. The functions $S_1(t)$ and $S_2(t)$ denote signals from the first and second channels of the DAC, respectively. The functions $a_1(t)$ and $a_2(t)$ denote the signals arriving at the first and second channels of the ADC, respectively.
Figure 5. Explanatory diagrams of DAC and ADC signals.

To carry out the experimental studies, a three-axis magnetic coil was placed on the foamed polystyrene with sides of 6x6x6 cm, and the width of the conductor was 270 μm (figure 6). Each of the three coils has 100 turns. The coils are oriented in three axes (XYZ). As a generator and receiver, a sound card was used for the SB Creative AudigySE PCI SB0570 personal computer. A three-axis sensor was placed on a two-coordinate scanner (figure 6).

Figure 3 shows a picture of the amplifier circuit for the source coils and receiver coils. The amplifiers are based on TDA2822M chips operating in the range of up to 50 kHz. The TDA2822M contains two amplifiers. Signals from the first chip go to two coils - the source. The signal from the DAC of the sound card is fed to the input of the chip. Two receiving coils are connected to the inputs of the amplifiers of the second microcircuit, whose outputs are connected to the LineIn input of the sound card.
Figure 6. Experimental setup.

Figure 7. Amplifier.

Figure 8 shows the test object. The test object consisted of a brass plate 300 μm thick, the step size of the object was 5 cm.

Figure 8. Test object in brass with a thickness of 300 μm.

Figure 9 shows the result of measuring the signal passing from the X-oriented coil to the Y-oriented coil. Figure 10 shows the measurement result of the signal passing from the X-oriented coil to the Z-oriented coil. Figure 11 shows the measurement result of the signal passing from the Y-oriented coil to the Z-oriented coil. The cosine quadratures of the signals are shown. In Figure 12, the result of measuring the signal of the modulus of the vector by the formula $\sqrt{|U_{XY}|^2 + |U_{XZ}|^2 + |U_{YZ}|^2}$.
5. Conclusion
It can be seen that the results of the experiment are in good agreement with the results of numerical simulation, which confirms the correctness of the chosen mathematical model of a three-axis magnetic induction sensor. On the reconstructed image modulo (XYZ), one can distinguish the contour of an electrically conductive object and recognize its shape.

Acknowledgements
The work was supported by the Grant of the Russian Science Foundation No. 16-19-10272.

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