Modeling of physical processes during the propagation of ultrasonic waves in metallic media

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Abstract. The paper deals with the features of modeling physical processes during the propagation of ultrasonic waves in metallic media. A mathematical model for the propagation of shear vertical (SV) ultrasonic waves generated by a single element of a 32-element electromagnetic acoustic phased array has been developed. The calculation of the acoustic field of the 32-element SV electromagnetic acoustic transducer (EMAT) phased array was made. The total displacements for models with defects and without them were calculated. A computer simulation of the process of reflection of the ultrasonic beam from a defect was made. The developed model allows one to study the influence of shape, size, location of defects in the plate as well as the plate geometric parameters on the formation of the reflected signal.

1. Introduction
One of the tasks of applied physics is the determination of internal defects in metallic media. The complexity of the search and identification of defects depends on the metal structure location and the surface state of a test object. In order to identify such defects, non-destructive testing methods are used. Among these are ultrasonic, radiowave, magnetic, thermal, optical, eddy current, electric, radiation and capillary methods [1-9].

Ultrasound testing (UT) methods are considered as the most commonly used and high-speed ones [1, 2, 10-14]. Their use allows us to conduct investigations both within and beyond the laboratory [10-16]. The need to provide an acoustic contact between ultrasonic transducers and the test medium is the main limitation in the application of UT methods. Therefore, the development of non-contact methods for the generation and reception of ultrasonic waves in metallic media, which have found a large number of practical applications, is currently of particular importance [11, 14-16].

One of the solutions to this problem is the application of the UT method using electromagnetic acoustic transducers (EMATs) on a phased array. These devices are successfully used for various tasks [17-19]. The use of EMAT allows one to search for defects in metal structures and welds without the use of contact fluid and surface cleaning [2, 13-15].

Most of the previously developed EMAT designs where the ultrasonic beam can be electrically directed or deflected consist of a magnet on top of a meander coil. These structures consist of only one active element or coil, so they are very convenient for their simplicity. However, the central beam of the ultrasonic radiation pattern is controlled by changing the central frequency, which greatly limits the resolution (i.e., the system's ability to eliminate defects) and control capabilities. The aim of this work is the development of a 32-element EMAT phased array model where the ultrasonic beam can be electrically steered. The main advantage of this model is the possibility of focusing and angular scanning of an ultrasonic beam, which allows the study of hard-to-reach areas of the test object.
The mathematical modeling plays an important role in the development of ultrasonic transducers, as well as phased arrays. At the design stage, you can identify the design disadvantages of transducers and determine the patterns of interaction of ultrasonic waves with defects of various types. This significantly saves time and reduces construction costs.

Finite element modeling is an effective method for calculating the acoustic fields of ultrasonic transducers and phased arrays. One of the most functional and promising software environments for modeling physical processes is the COMSOL Multiphysics environment. This software environment allows the calculation of electric, magnetic, electromagnetic and acoustic fields, which generally enable complex modeling of EMATs [20, 21].

2. EMAT phased array design
This work considers the EMAT, which consists of a permanent magnet and a 32-element phased array. The phased array consists of 32 loop elements (8 elements in each layer) offset relative to each other by the radiating element width in the direction of the two axes of the plane (in the direction of the coil width, the offset is reset every 4 elements) (Figure 1). Each element of the phased array excites a signal with a certain delay relative to the neighboring element. Depending on the delay, the focus angle of the ultrasound beam changes (from all sources).

Alternating eddy currents are induced in the test object by inductance coils through which alternating current flows. The eddy currents interact with the bias magnetic field from the EMAT magnet and generate Lorentz force components normal to the eddy currents and the bias magnetic field. These force components generate shear waves in the sample [14, 22].

3. Development of a model for ultrasonic wave propagation from a single element of an EMAT phased array
The model of the single element of the EMAT phased array was simulated in Comsol Multiphysics 5.2 (COMSOL Inc., Massachusetts, USA) using the Solid Mechanics interface of the Structural Mechanics module model library and Magnetic field interface of the AC/DC module model library. The three-dimensional model consists of a permanent magnet, a current loop and a sample (Figure 2).

Figure 1. EMAT phased array configuration. The circles and crosses indicate that the currents in the coils leave and enter the figure plane, respectively.

Figure 2. Model for calculating the acoustic field of a single element of the EMAT phased array of SV-wave.
The dimensions of the magnet cross-section are $22 \times 4.5$ mm$^2$. The hemispherical steel sample 120 mm in diameter are simulated beneath the magnet and the coil. The gap between the magnet and the sample is 2 mm. The gap between the coil and the sample is 0.5 mm. Finally, the model is enclosed in a hemispherical domain 120 mm in diameter modeled as air and surrounded by magnetic insulation boundaries. The main parameters of the developed model are shown in Table 1.

Table 1. The main parameters of the developed model

| Parameter                              | Symbol | Value | Unit  |
|----------------------------------------|--------|-------|-------|
| Frequency                              | $f_0$  | 1     | MHz   |
| Longitudinal-wave speed                | $C_l$  | 5905  | m/s   |
| Shear-wave speed                       | $C_s$  | 3200  | m/s   |
| Density                                | $\rho$ | 7810  | kg/m$^3$ |
| Wavelength                             | $\lambda$ | 3.2 | mm |
| Coil step                              | $d$    | 1.6   | mm    |
| Width of the radiating element         | $e$    | 0.8   | mm    |
| Wire diameter                          | $d_r$  | 0.1   | mm    |
| Gap between the coil and the sample    | gap    | 0.5   | mm    |
| Current flowing in one loop            | $I$    | 0.1   | A     |
| Number of turns                        | $N$    | 5     |       |
| Sample radius                          | $R$    | 60    | mm    |
| Remanence                              | $B_r$  | 1     | T     |
| Electrical conductivity                | $\sigma$ | 4.032 | MS/m  |

The boundary condition ”magnetic isolation” is set at the external boundaries of the sphere, which sets the tangential components of the magnetic potential equal to zero at the boundary and is given by the equation

$$n \times A = 0,$$

where $n$ is the normal vector; $A$ is the magnetic vector potential.

The magnetic field of a permanent magnet is set using the ratio

$$B = \mu_0 \mu_r H + B_r,$$

where $\mu_0$ is the magnetic constant; $\mu_r$ is the relative magnetic permeability; $B_r$ is the remanence.

The dimensions of the magnet cross-section are $22 \times 4.5$ mm$^2$. The remanence is $B_r=1$ T and is directed along the y-axis.

The current in the coil is set by the equation

$$J_e = \frac{N I_{coil}}{s} e_{coil},$$

where $I_{coil}$ is the current flowing in one loop; $N$ is the number of turns; $s$ is the coil wire cross-section area; $e_{coil}$ is the local coil direction.

The mesh elements of the model had a triangular shape and a maximum length (distance between the furthest nodes) of less than 0.1 mm under the coil. The length of the elements was increased progressively until the elements furthest from the coil and the magnet reached a maximum length of 6 mm. A convergence test was conducted to confirm that the results did not change by more than 1% when using a finer mesh; this value was selected by the authors as a good compromise between accuracy and run length of the simulation. The skin depth of the height is 2.1 mm (equal to the thickness of the skin layer) was built in the sample at the sample-air interface. Since eddy currents are excited in this
layer, this region requires a high degree of mesh discretization for an accurate result. The propagation of an acoustic wave in a hemispherical steel sample is shown in Figure 3.

![Figure 3](image)

**Figure 3.** The propagation of an acoustic wave in a hemispherical steel sample.

The analysis of results (Figure 3) shows that four types of waves can be observed, surface waves of Rayleigh, longitudinal waves, shear waves, and head waves. Surface waves of Rayleigh are spreading only along the surface. Therefore, they cannot be used to investigate defects inside the sample [23, 24]. It has been that longitudinal and shear waves have different speeds and propagate at different angles.

4. Development of a model for the interaction of ultrasonic waves with defects

A model of a 32-element EMAT phased array of SV waves is used to simulate an ultrasonic wave reflected from various types of defects (Figure 4).

The two-dimensional model can be used to calculate the acoustic field in a plate with defects extended in the same direction as single elements of the phased array (for example, lateral through-hole drilling). In this case, the acoustic wave is considered in the plane strain approximation. Plane strain is relevant when the 2D model can be considered as a cut through an object which is long in the out-of-plane direction [13]. This approximation makes it possible to calculate the acoustic wave reflected from the defect with less run length of the simulation.

![Figure 4](image)

**Figure 4.** EMAT phased array model for calculating the acoustic field reflected from through defects.

The excitation signal consisted of a 1-cycle Hann pulse. The «Prescribed displacement» condition is used to create tangent or normal displacements when the longitudinal and transverse waves are excited. The displacements are prescribed by the equation

\[ U = \frac{1}{2} U_o \sin(\omega t) \left(1 - \cos\left(\frac{\omega t}{n}\right)\right) \text{rect}(f_o t) \]  

(4)
where $U_0$ is the displacement amplitude calculated when modeling a single element; $\omega = 2\pi f$ is the angular frequency; $n$ is the number of cycles; $\text{rect}(x)$ is the rectangular window.

The mesh elements of the model have a triangular shape and a maximum length (distance between the furthest nodes) of less than 0.3 mm.

The Low-Reflecting Boundary condition was used for the lateral boundaries of the plate since it is assumed that the plate dimensions in two directions are much larger than the thickness. Figure 5 shows the propagation of an acoustic wave in the plate after reflection from the defect at a time instant of 15 $\mu$s. The color legend shows the total displacement at points on the surface.

![Figure 5. Total displacement distribution after reflection from the defect](image)

The analysis of the results obtained shows that when a purely longitudinal or purely shear wave of vertical polarization falls on the metal-air boundary, the resulting fields contain both longitudinal and shear waves. Obviously, the wave nature does not change during a normal fall. When a shear wave is reflected from a defect, two waves (shear and longitudinal) are formed (Figure 5). Because of this, there are two responses from the defect in the total displacement plot (Figure 6), the first is a longitudinal wave, and the second is a shear wave. Figure 6 shows the time dependence of the total displacement for models with and without defects.

![Figure 6. Time dependence of the total displacement for models with and without defects](image)

The analysis of the dependencies (Figure 6) shows that in the region of 20–30 $\mu$s, the difference in the nature of change in the graphs allows us to reveal the presence of a defect.

5. Conclusions
Based on the calculation data obtained for the simulation of physical processes of ultrasonic waves propagation in metallic media, the 32-element EMAT phased array of SV-waves was developed. It has
been found that the high degree of mesh discretization is required in the skin depth region of the developed EMAT phased array model for accurate calculations. Analysis of the computer simulation results of ultrasonic beam reflection process from a defect allows us to establish the following. After SV-wave reflects from a defect, two waves (shear and longitudinal) are formed. The presence of a defect can be revealed by registering these waves. The developed model will make it possible to study the influence of shape, size, defect location in the material on the reflected signal formation during tests with a real sensor.

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