Modeling of physical processes of interaction of ultrasonic wave with metal structures for detection of defects

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Abstract. In the article the features of the physical processes modeling of the ultrasonic wave interaction to the metal structures are considered. The mathematical model for calculating the acoustic field of a single element of a 32-element electromagnetic acoustic phased array of \textit{SV}-waves is developed. The computer simulation of the process of reflection of the ultrasonic beam from a defect is carried out. The developed model allows to study the influence of the shape, size, location of defects in the plate, as well as the geometric parameters of the plate, on the formation of the reflected signal.

1. Introduction
Currently, an important urgent task is the timely diagnosis of damage in hard-to-reach welded joints of various metal structures (for example, pipelines, beams, etc.). The greatest difficulty arises with the detection of internal defects due to the fact that they are located inside metal structures and are not available for the visual inspection. The various methods are used for the identify these defects [1, 2]. The most preference is given to non-destructive testing methods (ultrasonic, radiowave, magnetic, thermal, eddy currents, electric, etc.), which are also used in various fields for diagnosing the state of media [1-6]. The special place among them is occupied the methods with the using of the laser radiation and the optical systems [7-11]. All of them are successfully implemented in the laboratory. It is most appropriate to use the electromagnetic acoustic method with the using of the electromagnetic acoustic transducer (EMAT) phased arrays for the defect determination a during the working at high altitudes. At present, the phased arrays are widely used in various fields of science and technology [12-15], where them have proved their necessity.

The essence of this method lies in the fact that during the bias magnetic field interacts with eddy currents that are induced in the metal of the controlled sample during the alternating current passing through the coil is formed the Lorentz force. The Lorentz force components generate shear waves in the sample [16, 17].

The most appropriate solution for diagnosing welded joints and metal structures is to use a 32-element EMAT phased array. In our work, the coils are used as elements of a phased array. We are researching the shear vertical (SV) waves, since them do not require the creation of the complex
multipolar magnetic systems and the coils with the complex topology, and they have all the advantages of shear horizontal (SH) waves [18].

The mathematical modeling plays the important role in the development of the phased arrays. At the design stage, the modeling using allows to identify the flaws in the transducers design and to determine the ultrasonic waves interaction patterns with the defects of the various types [18-21]. This significantly saves the time and reduces the costs to the construction.

At present, for modeling magnetic and acoustic fields a large number of methods and algorithms are used [22-30]. The done analysis by us showed that the most effective way of calculating the acoustic fields of the ultrasonic transducers and the phased arrays is the finite element method (FEM). The COMSOL Multiphysics medium is one of the most functional and promising software environments for modeling physical processes. This software medium allows to calculate the electric, the magnetic, the electromagnetic and the acoustic fields. This gives the whole an opportunity to conduct a comprehensive simulation of EMATs [21, 22, 31].

2. The design of the phased antenna array

The main advantages of multi-element EMAT phased arrays are the ability to control various parts in hard-to-reach places and the ability to electronically control the angle of entry and focusing of the ultrasonic wave into the selected area. In other words, irradiation and reception of echo signals occur at different angles to the discontinuity, so that we can find out accurate information about the shape and size of the defect.

However, ultrasonic testing using phased array transducers is rather slowly being introduced into modern technologies due to the complex construction of the transducer, its high cost and lower reliability (compared to single-element transducers) [21, 31].

A phased array is a set of point sources that excite signals with a certain delay relative to the neighboring element. Depending on the delay, the focus angle of the ultrasonic beam changes (from all sources) [31-33].

The time delays $dt_i$ when the beam is focused on the angle $\alpha$ can be expressed as:

$$ dt_i = \frac{10^3 dr_i}{c_t}, $$

$$ dr_i = \sqrt{(x + (n - 1)d)^2 + h^2} - \sqrt{(x + (i - 1)d)^2 + h^2}, $$

$$ x = htg(\alpha) - \left(\frac{n}{2} - 0.5\right) d, $$

where $n$ is the number of elements of the phased array; $d$ is the distance between elements; $h$ is the focusing depth; $\alpha$ is the focusing angle; $dr_i$ is the distance from an element with the number $i$ to a circle of radius $\sqrt{(x + nd)^2 + h^2}$ centered at the focus point; $c_t$ is the velocity of the shear wave.

![Figure 1](image_url)  

**Figure 1.** The configuration of the EMAT phased array.

In this work, we use a phased array, which consists of 32 loop elements (8 elements in each layer), offset relative to each other by the width of the radiating element in the direction of the two axes of the plane (the offset is reset every 4 elements in the direction of the width of the coil) (Figure 1).
3. Development of a model of a single element 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). The model is enclosed in a hemispherical domain modeled as air, which has a diameter of 120 mm and is surrounded by magnetic insulation boundaries. The main parameters of the developed model are shown in table 1.

![Figure 2. Model for calculating the acoustic field of a single element of the EMAT phased array of SV-waves.](image)

![Figure 3. Boundary layer at the air-metal boundary.](image)

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

The current in the coil is set by the equation

$$J_e = \frac{N_{\text{coil}}}{S} e_{\text{coil}},$$

where $I_{\text{coil}}$ is the current flowing in one loop; $N$ is the number of turns; $S$ is the coil wire cross-section area; $e_{\text{coil}}$ is the local coil direction [32].

For describing the elastic properties of a material, the following parameters are used: the sample density $\rho$, the velocity of the shear wave $C_s$, and the velocity of the longitudinal wave $C_l$. The main parameters of the developed model are shown in table 1.

The mesh elements of the model have 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. The maximum length is less than 0.5 mm in the sample. A convergence test was conducted to confirm that the results did not change by more than 1 % when using a denser mesh; the authors selected this value as a good compromise between accuracy and run length of the simulation. A boundary layer 2.1 mm high, equal to the skin depth, was built in the sample on the border with air (Figure 3). Since eddy currents are excited in this layer, this region requires a high degree of mesh discretization for an accurate result.

The propagation of the acoustic wave in a steel hemispherical sample is presented in Figure 4. Analysis of the results 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 lengthwise. Therefore, theirs cannot be used to research defects inside the sample [31-33].

It is established that longitudinal and shear waves have different speeds and propagate at different angles.

| 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            | \( \text{gap} \) | 0.5   | mm         |
| Current flowing in one loop                    | \( I \)   | 1000  | A          |
| Number of turns                                | \( N \)   | 5     |            |
| Sample radius                                  | \( R \)   | 60    | mm         |
| Remanence                                      | \( B_r \) | 1     | T          |
| Electrical conductivity                        | \( \sigma \) | 4.032 | MS/m       |

![Figure 4. The propagation of an acoustic wave in a steel hemispherical sample.](image)

### 4. Development a model of the ultrasonic wave interaction with defects

For the simulate of the ultrasonic wave reflected with the various defects types in our work we are using a model of a 32-element EMAT phased array of SV waves. All models (for various defects) are parameterized, so it is possible the calculation of the different thickness plates for the particular from 6 mm to 32 mm, and the defects of the various sizes.

The excitation signal consisted of a 1-cycle Hann pulse. The during simulating the excitation of an acoustic wave, the excitation signal consisted of a 1-cycle Hann pulse (Figure 5).

The «Prescribed displacement» condition is used to create tangent or normal displacements when the longitudinal and shear waves are excited. The displacements are prescribed by the equation

\[
U = \frac{1}{2} U_0 \sin(\omega t) \left( 1 - \cos \left( \frac{\omega t}{n} \right) \right) \text{rect}(f_o t),\tag{5}
\]

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.
Figure 5. The excitation pulse.

The during modeling of the acoustic fields by FEM, it is necessary to comply with the convergence condition by Courant-Friedrichs-Lewy, and also take into account the state for the ratio of the size of the finite elements to the wavelength, which should be at least one fifth. In any model that contains the acoustic wave propagation, the following inequality must be implemented:

\[ C\Delta t < \Delta x < \frac{C}{5f}, \]  

where \( C \) is the wave velocity; \( \Delta t \) is the time sampling step; \( \Delta x \) is the distance sampling step (maximum size of finite elements).

The mesh elements of the model had a triangular shape, and the maximum length (distance between the furthest nodes) is less than 0.5 mm in the sample. 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.

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 [12]. This approximation makes it possible to calculate the acoustic wave reflected from the defect with less run length of the simulation.

The simulation results are presented in Figure 6. The propagation of the acoustic wave in a plate before reflection from the defect is shows in Figure 6(a). The propagation of the acoustic wave in a plate after reflection from the defect is shows in Figure 6(b).

The dependence of the total displacement on time is established. The analysis results of the dependence (Figure 6 and Figure 7) are showed that the signal reflected from the defect comes at the center of the phased array in 17.5 \( \mu \)s after the start of radiation.

Figure 6 (a, b). The total displacement distribution before reflection from the defect (a) after reflection from the defect (b).
Figure 7. The dependence of the total displacement on time in the center of the phased array.

The longitudinal wave is greater the lower boundary of first and is reflected from it since the it velocity is greater than the other waves. The longitudinal waves reflected from the bottom of the plate come to the center of the array together with the wave reflected from the defect. In thin plates, this has a more significant effect on the result than in thick ones, since the amplitude of the reflected wave will be greater. Longitudinal waves will also significantly affect the result when the defect is close to the sample boundary. Since time delays are set to focus the shear waves, the excited longitudinal wave will be much smaller in amplitude and will not have a significant effect on the results.

4. Conclusions
The obtained results of the physical processes modeling of the ultrasonic wave interaction with the metal structures are showed that the developed model by us allows to research the influence of the shape, the size, the defects location in the plate, as well as the geometric parameters of the plate, on the reflected signal formation.

5. References
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