Numerical simulation of electromagnetic-acoustic transformation using Jiles-Atherton magnetic hysteresis model

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Abstract. The paper presents the results of numerical simulation of electromagnetic-acoustic transformation using Jiles-Atherton magnetic hysteresis on the example of excitation and reception of a transverse wave through the thickness of the reference block CO-2 based on the W-shaped magnetic core and inductor in the form of a meander coil with in-phase conductors. Distributions and graphs of time dependence for the magnetic field, the field of eddy currents and the field of elastic deformations are given in comparison with the classical modeling approaches. Satisfactory convergence of the simulation results with experimental data was established by the example of the signal received by the inductor, the distribution of the normal component of the magnetic flux density in the gap of inductor positioning and the calculated double transformation coefficient.

1. Introduction
The ultrasonic method of non-destructive testing is widely spread in modern industry, since it can be applied to identify defects in the most critical products used in oil and gas, aerospace, and railway industries. The ultrasonic method of non-destructive testing has a large number of advantages among the types and methods of non-destructive testing. The use of various types of waves in metal provides the sphere of application of ultrasonic testing not only for flaw detection but also for health structure monitoring, thickness measurement, and estimation of strain-stress state [1-3].

One of the most widely used transducer for excitation and reception of ultrasonic waves is electromagnetic-acoustic transducer (EMAT), which principal advantage over piezoelectric transducers is measurement without usage any couplant [4-8]. They do not require any coupling media, since a wave is generated directly in the specimen rather than in the transducer. Moreover, various combinations of coils and magnetic systems allow to generate the waves of various types [9]. These benefits contribute to large-scale implementation of EMATs for ultrasonic testing.

As of today, a great number of works deals with the EMAT simulation based on the FE-analysis, where distribution of magnetic flux density, eddy current fields in the specimen, and elastic displacements of ultrasonic waves under the action of Lorentz force are studied and described [10-15]. However, these models disregard non-linear properties of ferromagnetic materials or account only for
magnetization curve, which may significantly affect the convergence of theoretical and experimental study.

To improve validity of the processes that occur in metals under exposure to the EMAT electromagnetic field, the simulation domain is required to be expanded in terms of properties of the magnetic material, and, as a result, the EMAT system model is required to be enhanced by simulation of hysteresis cycles. The relevant models and methods may be used to design the EMAT magnetic bias system ensuring high-accuracy reproducibility of theoretical and experimental data.

There exists a number of models accounting for non-linear properties of magnetic materials, the best known being Rayleigh loop model, Jiles-Atherton model, Preisach model, Chan-Vladirimescu model, and Hodgdon model [16-24]. The Jiles-Atherton model is premised on a theory of ferromagnetic hysteresis, which defines the hysteresis function of the anhysteretic magnetization curve [24-25]. Intensity of magnetization is represented in the model as a concentrated change in magnetic state when magnetic field is applied to the magnetic material with equivalent magnetic flux.

The article presents an outcome of simulation of the processes that occur in the EMAT for bulk transverse waves, with due account for non-linear magnetic properties of the materials used for both the specimen and the magnetic core, within the time domain problem, using the Jiles-Atherton model.

2. Finite element model description

The electromagnetic-acoustic transformation was simulated using the Jiles-Atherton model described in the article [24]. Its principal advantage is high accuracy of building the saturated hysteresis loop, high accuracy of generating the energy-loss model and its transfer over all domains, as well as the fact that the model accounts for a temperature dependence. The model makes the parameter extraction possible and is highly implementable in various software, particularly, in COMSOL Multiphysics.

When setting a problem, the design of the EMAT for excitation and reception of a bulk transverse wave was selected as an initial model. The model configuration (figure 1a) includes a meander-coil with 18 turns, a bias coil wound around a W-shaped magnetic core, and the specimen, where an acoustic wave propagates.

![Figure 1](image_url)

**Figure 1.** Formulation of the finite element model (a) and finite element mesh (b)

The magnetic core and the specimen were specified with non-linear properties of the material, according to the Jiles-Atherton model, which are provided in Table 1. Electromagnetic properties of other materials are provided in Table 2.

The magnetic core was made of permendur (49Fe-49Co-2V) with high saturation flux density, whereas the specimen was made of low-alloyed steel 20 (Steel 1020, AISI). The magnetic hysteresis loops were selected and calculated using the software Roman Szewczyk [26] adjusted for environment Matlab.
Modeling the processes of propagation of elastic displacements was carried out only in the specimen, for which the elastic and mechanical properties were presented in Table 3.

Number of turns in the bias coil is 1700 and in the excitation and receiving coil (inductor) is 18. Rated current in the bias coil is $I_1 = 2$ A, whereas peak current in the inductor is $I_2 = 30$ A. The pulse shapes are represented in Figure 2.

| Table 1. Jiles-Atherton model material parameters. |
|-----------------------------------------------|
| Material | Saturation magnetization, $M_s$ (A/m) | Langevin slope, $a$ (A/m) | Interdomain coupling, $\alpha$ | Pinning parameter, $k$ (A/m) | Reversibility, $c$ |
|----------------|---------------------|------------------|-----------------|-----------------|-----------------|
| Fe-Co-V alloy    | $1.9 \cdot 10^6$   | 40               | $1 \cdot 10^{-4}$ | 160             | 0.02          |
| Steel 1020       | $1.25 \cdot 10^6$  | 50               | $3.5 \cdot 10^{-5}$ | 320             | 0.005         |

| Table 2. Jiles-Atherton model material parameters. |
|-----------------------------------------------|
| Material | Relative permeability, $\mu$ | Electrical conductivity, $\sigma$ (S/m) | Relative permittivity, $\varepsilon$ |
|----------------|----------------|-----------------|-----------------|
| Air            | 1              | 0               | 1               |
| Copper         | 1              | $5.998 \cdot 10^7$ | 1               |
| Fe-Co-V alloy  | not used       | $2.6 \cdot 10^7$    | 1               |
| Steel 1020     | not used       | $8.41 \cdot 10^6$    | 1               |

| Table 3. Elastic and mechanical material properties. |
|-----------------------------------------------|
| Material | Young’s modulus, $E$ (Pa) | Poisson’s coefficient, $\nu$ | Density, $\rho$ (kg/m$^3$) |
|----------------|-----------------|-----------------|-----------------|
| Steel 1020   | $210 \cdot 10^9$ | 0.281         | 7850            |

Figure 2. The shapes of biasing current (a) and probe pulse (b).

One of the conditions for the proper result is size of the mesh (Figure 1b), defined by the mesh spacing. No special requirements were imposed during simulation of the bias field; therefore, the default mesh was plotted. The mesh spacing for simulation of propagation processes was selected based on the Courant-Friedrichs-Lewy condition; herewith, at least 5 finite elements accrued to one wave length at velocity of the transverse wave propagation of 3,250 m/s.

The number of finite elements totalled to 267,146 (Figure 1b), that of degrees of freedom for the problem to be solved – to 970,947.

The simulation results were visualized by means of plots of magnetic flux density, eddy currents, and elastic displacements against time in the point on the surface of the specimen below the midpoint.
of the inductor. The double transformation coefficient was evaluated also by means of a plot of the current density vector on the inductor integrated on the all of edges.

3. Experimental setup
The experimental setup (Figure 3) included a synchronization unit, a probe pulse generator, a DC generator, an electromagnetic-acoustic transducer, a band-pass filter, a high-frequency amplifier, and an analog-to-digital converter built into a personal computer. The probe pulse generator provides a probe pulse amplitude of up to 2 kV, and an electromagnetic-magnetic transducer biasing system, consisting of 1,700 turns of copper wire, allows to create a bias field in the gap of inductor positioning of up to 2 T. Its resistance was 24 Ohms, which due to the 48 V voltage generated by the DC generator allows to get a current of 2 A. The inductor in the form of a meander with in-phased conductors consisted of 18 turns with an aperture of 15 mm and a width of 0.4 mm for each conductor.

![Figure 3. A scheme of the experimental setup](image)

The measurement result was a signal of a series of multiple reflections from plane-parallel surfaces in the specimen. The reference block CO-2 was used as the specimen. A bulk transverse wave was excited, propagating through the thickness of a reference block which was 30 mm.

To measure the normal component of the magnetic field in the gap of the inductor positioning, a TPU-05 magnetometer with a Hall sensor was used. The measuring probe with the Hall sensor was located in the middle of the magnetic field concentrator of the W-shaped magnetic core and moved in the range from -20 to 20 mm in the horizontal direction with a step of 1 mm. The value of the normal component of the magnetic flux density was measured twice in the forward and reverse directions and the average value was calculated.

4. Results and discussion
As a rule, permanent magnetic field is concentrated on the edge of sharp angles and, in the frequency domain, distributed over the surface of ferromagnetic bodies (Figure 4b); herewith, the higher the frequency, the lower depth of magnetic field penetration. In the time domain problem, the magnetic field distribution depends on velocity of transient processes, which defines frequency spectrum of the magnetic field. Therefore, the magnetic field in the time domain is concentrated on sharp angles and decays exponentially into the depth of ferromagnetic materials (Figure 4a), with the nature of decay depending on biasing type and method.

Eddy currents are generated only in the frequency domain, and depth of their penetration into electrically conductive medium depends on frequency of the electric field similarly to magnetic field in the ferromagnetic medium. Since magnetic and electric fields are interconnected, eddy currents in
the time domain are concentrated on the surface of electrically conductive media at adjacent portions near the alternating current or alternating magnetic field source. Therefore, peak eddy currents can be observed below the inductor for the specimen and the bias coil for the magnetic core (Figure 5a).

The pattern of elastic displacement distribution shows horizontal (tangential) and vertical (normal) components (Figure 5b), which dominance in a certain domain area, location, and time may determine the wave type.

![Figure 4. Distributions of the magnetic field density calculated by using Jiles-Atherton magnetic hysteresis (a) and BH-curve (b).](image1)

![Figure 5. Distributions of the eddy current (a) and displacement field (b).](image2)

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The plot of magnetic flux density against time (when current increases in the bias coils, it essentially means increase in intensity of external magnetic field) represents a classical magnetization curve (Figure 6a). Herewith, when \( t = 0.3 \) s, the specimen is in saturated state, and an electric pulse (Figure 2b) is sent to the inductor, the plot shows slight distortions of the magnetic field (Figure 6b), which size is defined by current and its direction.

When an electric pulse is sent to the induction coil, eddy current surges sharply (Figure 6b), with the form of the surges corresponding to form of the electric pulse (Figure 2b), whereas its amplitude exceeds that of eddy currents generated by the magnetic bias system.

When an acoustic wave is generated, amplitude of elastic displacements is less in the initial pulse than in the first back wall signal due to the fact that, during generation of the acoustic wave, elastic displacements occur with slight hysteresis resulted from interaction between eddy currents and magnetic fields of the magnetic bias system and the induction coil. The hysteresis phenomenon is also
affected by irregular distribution of eddy currents on the surface of the specimen, resulting in displacements having different amplitude and direction at different depths.

To verify the simulation adequacy, current density was compared with the signal received by inductor on the EMA transducer (Figure 7a) and magnetic flux density was measured in the gap of the inductor positioning (Figure 7b). Both modelling results have satisfactory convergence with experimental data.

![Figure 6] Dependencies of the magnetic flux density (a) and eddy currents (b) vs time.

![Figure 7] Comparison of current density obtained by finite element modeling with the signal received by EMA transducer (a) and the graph of magnetic flux density in the gap between magnetic core and the specimen (b).

Also, a double transformation coefficient was calculated based on the ratio between magnitudes of the current-density vector at initial and back wall signals on the surface of the induction coil. Therefore, the double transformation coefficient amounted to $K^2 = 1.1 \cdot 10^{-6}$, which is compatible with theoretical data [27, 28].

5. Conclusions

Therefore, following the results of numerical simulation of electromagnetic-acoustic transformation, based on FE-analysis, using the Jiles-Atherton magnetic hysteresis model, it may be concluded as follows:
the simulation showed that the approach applied could be used for design of EMATs for bulk transverse waves, with due account for nonlinear magnetic properties of the materials used both for the specimen, and the magnetic core;

- validity of the simulation results was verified by numeric value of the double transformation coefficient, which was compatible with theoretical data.

The simulation results may be used for design, engineering, manufacturing, production, and modification of the EMATs for bulk transverse waves.

Further works may be focused on the studies regarding efficiency and comparison of electromagnetic-acoustic transformation for excitation and reception of waves of other types, dynamic biasing in the maximum permittivity domain, as well as influence of excitation parameters and different properties of the materials used both for the specimen, and the magnetic core on the double transformation coefficient.

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