A Two-Dimensional EMAT Code for Non-Magnetic Materials using a Coupled/Uncoupled Formulation

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Abstract

A previously introduced two-dimensional EMAT (Electro-Magnetic Acoustic Transducer) simulation code developed in-house at JAEA, based on both coupling/uncoupling of eddy currents and wave displacement in a non-magnetic material is analyzed against 3D numerical simulations and experimental wave displacements performed by JAPEIC. The experimental setup visualizes wave propagations along the vertical surface of a stainless steel plate using a piezoelectric sensor, while the 3D simulations were performed using an un-coupled model of EMAT based on two commercial codes: EMSolution for the eddy currents and COMWAVE for the wave propagation.

Keywords: EMAT, Ultrasonics, Finite Element, Eddy Currents, Electro-Magnetic Acoustic Transducer

1. Introduction

Previously, it was presented by JAEA a novel developed Finite Element Method (FEM) approach to Electro-Magnetic Acoustic Transducer (EMAT) simulation in a two-dimensional (2D) plane-parallel approximation, in which both electromagnetic and mechanical phenomena were coupled in a single FEM equation system [1]. The uncoupled code is based on the same FEM architecture as the coupled one, but at that time no experimental validation was offered for either code.

In this paper we therefore compare the results obtained with both the coupled and uncoupled JAEA codes with experimental wave propagation measurements made by JAPEIC [2]. In the simulation, we start from the previous reference EMAT setup, and progress towards the JAPEIC experiment step by step, focusing on the effect of several approximations including, but not limited to, the magnet configuration, the coil type and positioning, and the EMAT lift-off distance. Finally, the JAEA simulation results are also compared with those from 2D and three-dimensional (3D) simulations performed by JAPEIC using a combination of two commercial simulations software in an uncoupled way.

For reference, additional details about EMAT theory/ description and practical applications are described in [3].

2. Experimental visualization setup

The EMAT experimental setup was previously described in detail in [2], and is briefly summarized in Fig. 1. In comparison with the choices made during previous coupled EMAT work [1], the main differences are:

a) a single EMAT is used, and its elements are mounted without any additional shielding metal cage;

b) a double magnet structure is used vs. the previous single magnet design, and a racetrack coil is used vs. the previous meander coil with 5 turns;

c) the input signal is different (2GHz vs. 1GHz);

d) the test sample is made from stainless steel SUS316, which is similar to the ANSI316, and different from the previous aluminum plate.

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In the present paper, we analyze the effect of each of these differences individually.

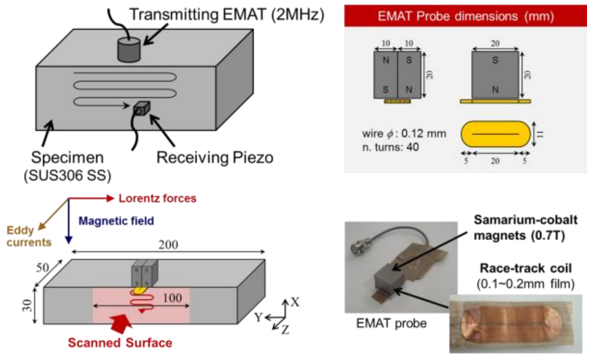


Fig.1. Description of the experimental EMAT visualization setup [2]

3. Simulations details

For reference, additional details about EMAT theory/ description and practical applications are described in [3].

Three different approaches (four codes) are used in the present work to solve the time transient EMAT problem:

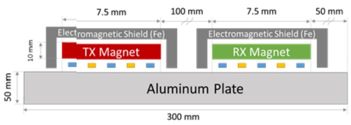
a) two EMAT-specific codes developed in-house by JAEA, 2DEMATc and 2DEMATu, which were previously presented in [1] and directly solve the EMAT coupled and uncoupled equations, respectively.

b) a combination of two commercially available software, which was previously used by JAPEIC to analyze their experimental results [2]: EMSolution [4], to simulate the eddy currents, and COMWAVE [5], to simulate the sound wave propagation inside the test material.

The uncoupled JAEA code, 2DEMATu, uses the conventional approach to solve the EMAT problem, by separating the electromagnetic and mechanical interactions in three distinct steps. The 2DEMATu code carries out the full EMAT calculation in a time-step by time-step basis. The third and last step of the EMAT simulation, the receiver coil signal, can only be computed with the JAEA code:

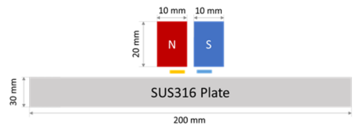
The new simulation domain is shown in Fig. 2, and it is an evolution from the one previously employed in [1].

Regarding the mesh, for this type of simulations [1], refinement in the test material surface was the key to prevent the appearance of large numerical instabilities on the edge. (2-million elements, λ_S/ 50 pitch mesh M3).



Property	Al	Fe
σ(MS/m)	35.5	10.4
ρ (kg/m³)	2700	-
μ_r	1	1000
G (Gpa)	25.9	81.8
λ(Gpa)	52.0	112.9

Add. Dimensions (mm)	
coil spacing	1
coil-magnet sep.	0.25
coil liftoff	1
shield spacing	1
shield thickness	2



Property	SUS 316
σ (MS/m)	1.35
ρ (kg/m³)	7980
μ_r	1
G (Gpa)	76.0
λ (Gpa)	89.2

Add. Dimensions (mm)	
coil track width	5
coil track sep.	1
magnet separation	0.250
magnet-coil sep.	0.125
coil height	0.125
coil liftoff	1

Fig. 2. Simulation domain for old previous work setup (up) and new experimental setup (down)

The newly adopted input current pulse [2] and that previously used in [1] are given in Fig. 3 left and right, respectively.

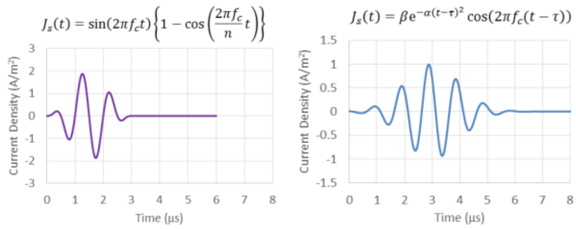


Fig. 3. Newly adopted (left) and previously used (right) input current density pulses

4. Analysis

One of the most noticeable differences between the new experimental setup and the previous one was the asymmetry of the EMAT-generated sound wave in the material [2].

The magnet configuration was changed from a single magnet element to a couple of magnets with opposite polarization. The results (see Fig. 4), made clear that this was the change originating the asymmetry of the wave, arising from the magnetic field asymmetry of the EMAT in the vicinity of the test sample surface.

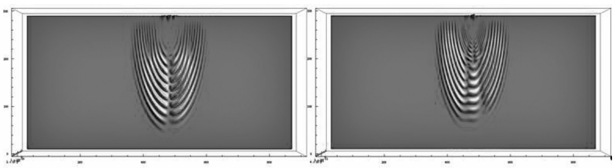


Fig. 4. Sound wave comparison between single (left) and double (right) magnet configuration

We had seen in previous work that the most noticeable difference between the coupled and uncoupled formulations of the EMAT problem was the decreased amplitude in the receiver-coil signal [1]. Altogether, the most significant change in Fig. 5 is the amplitude of the excited S-wave, which almost disappears when using the uncoupled code. It is worth noting here that in real life there is not such large amplitude difference between both, but our 2D setup can only properly reproduce the P-wave, as will be discussed later.

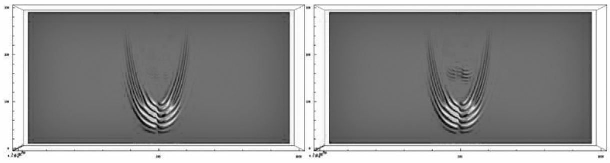


Fig. 5 Sound wave comparison between uncoupled (left) and coupled (right) 2D-EMAT codes

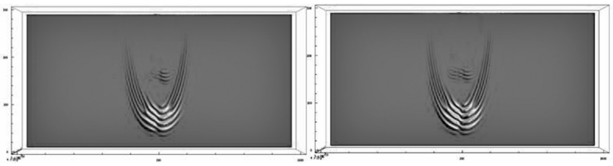


Fig. 6. Sound wave comparison between 0.5mm laterally shifted coils

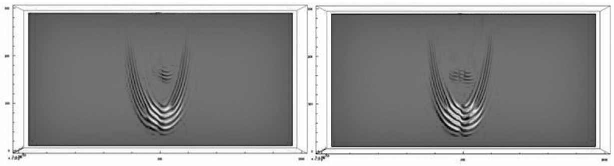


Fig. 7. Sound wave comparison between 1.0mm laterally shifted coils

When considering the wave asymmetry observed in the experimental signal [2], an unnoticed shift in the coil position was among the possible causes. As seen in Figs. 6-7, however, this effect is noticeable when shifting the coils to the left (towards the N magnet), but only minor when shifting to the right (towards the S magnet).

5. Comparison between simulations and experimental data

The comparison between simulation and experimental results at three different time instants is shown in Fig. 8. As seen in the figure, the initial longitudinal P-wave is well reproduced by the JAEA 2DEMATc code, both in amplitude and velocity, resulting in considerably similar figures. Other characteristic features such as the asymmetry of the experiment visualization could be also reproduced in the numerical simulation, which was confirmed to appear because of the asymmetry of the permanent magnets sources, creating an asymmetry in the Lorenz force inside the test material.

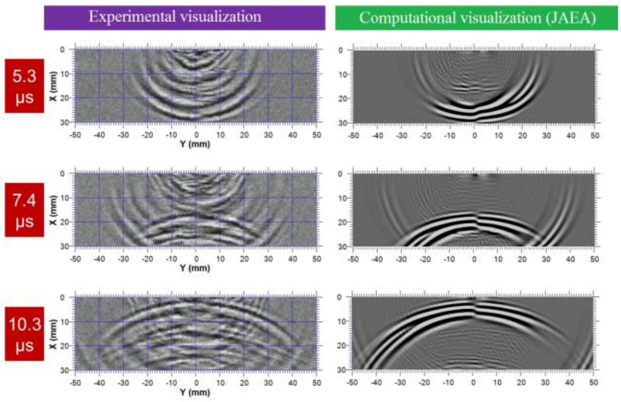


Fig. 8 Comparison between experimental sound-wave measurements and JAEA's 2DEMATc simulations

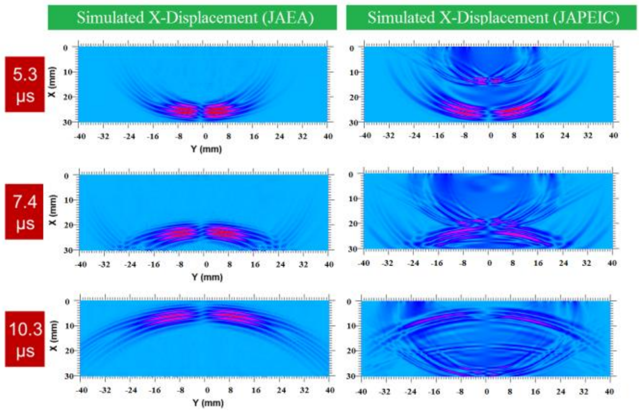


Fig. 9. Sound-wave comparison for X-component between JAEA's 2DEMATc code and EMsolution/COMWAVE results.

All in all, the results above highlight the limitations of the 2D plane-parallel code, into that only the longitudinal P-wave is excited. Indeed, the shear S-wave, which represents vibrations in the Z direction, perpendicular to the XY simulation domain, cannot be properly reproduced, because the Z-displacement component is ignored in the 2D approximation. This is even more clearly visible when comparing JAEA 2D coupled code (2DEMATc) results with those previously obtained by JAPEIC using a 3D version of COMWAVE, as seen in Fig. 9. The computational plot displays the absolute values of X component with both FEM approaches.

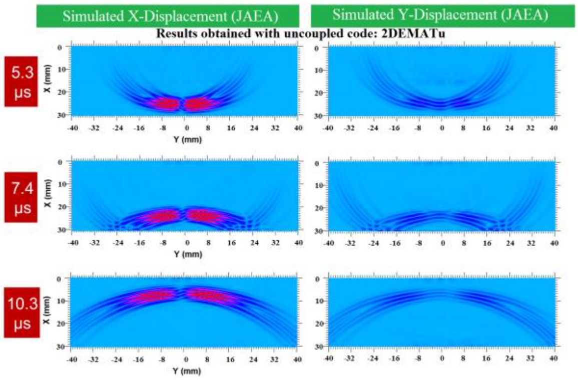


Fig.10. Sound-wave for X and Y-components computed with uncoupled JAEA's 2DEMATu code.

Finally, as one could have expected from the analysis in section 4, results obtained with JAEA 2D uncoupled code (2DEMATu) in Fig.10 show slightly smaller S-wave amplitude when compared with those obtained with 2DEMATc in Fig. 9.

6. Conclusion

It was shown that the JAEA developed 2DEMAT codes accurately reproduce the EMAT sound-wave propagation characteristics, both in terms of overall wave-figures and velocities. Simulation results were shown to be in good agreement with the experimentally observed waves, but only within the 2D approximation limitations. Indeed, because the plane-parallel configuration assumes no field variations in the direction perpendicular to the plane, the shear wave cannot be adequately reproduced. Similarly, Rayleigh waves propagating along the surface of the material cannot be simulated in this 2D configuration. Finally, for the present EMAT configuration, it is seen that the wave propagation in the coupled and uncoupled approaches to EMAT result in relatively small differences. The main advantage of the coupled code thus remains its reduced computational time, which in practical applications is several times faster than the uncoupled code. That is not only because it is inherently simpler (we solve a single FEM problem instead of 3 consecutive ones in the uncoupled code), but also because it offers better scalability when parallelized on multi-core CPUs. This advantage is even greater when compared with the concatenation of several commercial codes, but the latter approach already allows for simulations of actual 3D configurations, which are required for many practical applications.

References

[1] Daniel Garcia-Rodriguez, Ovidiu Mihalache, Masashi Ueda, "EMAT Simulations based on a Two-Dimensional FEM Coupled Electro-Mechanical Formulation", International Journal of Applied Electromagnetism and Mechanics, Vol 45, 2014, pp. 543-549.

[2] T. Yamamoto, T. Furukawa, I. Komura, R. Urayama, T. Uchimoto and T. Takagi, "Property study on EMATs with visualization of ultrasonic propagation", M. Bieth (Ed.), Proceedings of the 10th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, pp. 902-909, European Union (2014).

[3] M. Hirao and H. Ogi, "EMATs for science and industry: Non-contacting ultrasonic measurements", Boston / Dordrecht / London, Kluwer Academic Publishers, 2003.

[4] EMSolution software (http://www.ssil.co.jp/em/EMSolution/ja/index.html), 2015.

[5] Y. Ikegami, Y. Sakai and H. Nakamura, "A Highly Accurate Ultrasonic Simulator Capable of Over One Billion Elements for Non-destructive Evaluations," Proceedings of the 7th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressurized Components, 2009, pp. 177-190.