

Hybrid Modeling FEM-PEEC of Induction Heating System for Structures Having Heterogeneous Dimensions

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The aim of this study is to develop an Integro-Differential approach, specifically the coupling of the Finite Method (FEM) with the partial element equivalent circuit (PEEC), capable of efficiently modeling a contactless electromagnetic induction heating system (CEIH) for performing localized heat treatment in structures with heterogeneous dimensions. Thermal calculations using conventional methods, such as the finite element method, require significant computation time due to the relative movement of the excitation coil along three spatial axes, its inclination, the heterogeneous dimensions of the treated workpiece, and the high precision required for the heat treatment. This paper investigates the computational process of induction heating and identifies the root cause of inefficiency in conventional electromagnetic-thermal methods. To address this, a direct FEM-PEEC coupling method is proposed to calculate the three-dimensional eddy current distribution by meshing only the active parts of the domain, excluding the air region. This approach enables the heat flux to directly serve as input for temperature field calculations. Furthermore, the paper introduces a framework for handling large-scale or multi-coil configurations. The results show that the proposed methodology significantly reduces execution time while maintaining high precision. Its effectiveness was validated by comparing the outcomes with those obtained using the numerical method (Flux 3D Software).

Index Terms—Contactless electromagnetic induction heating System, Heterogeneous dimensions, Integro-Differential, Modelling, Partial element equivalent circuit method.

I. INTRODUCTION

Local induction heating or contactless electromagnetic local induction heating is a process of heating a specific area of a material using electromagnetic induction. This is achieved by placing the material in a high-frequency magnetic field generated by an induction coil. The magnetic field induces eddy currents within the material, which in turn generate heat due to the material's electrical resistance. Local induction heating is widely used in industrial applications, such as metalworking, welding, and heat treatment, where precise and controlled heating is required [1]. The amount of heat generated is determined by factors such as the material's electrical conductivity, magnetic permeability, the frequency and power of the electromagnetic field, the shape and position of the induction coil and topology of workpiece. The induction heating process includes electromagnetic induction and heat conduction. It is tough to obtain the temperature distribution of the workpiece during induction heating through a theoretical method and experiment-based methods are too costly. Therefore, numerical simulation has become an effective solution for obtaining the temperature fields of induction heating. A typical geometrical model for induction heating simulation is presented in Fig. 1. Over the last decade, several studies have focused on improving calculation efficiency and minimizing simulation time. Heat source models have been developed based on experimental results [2], utilizing methods such as empirical formulas [3], artificial neural networks [4], quasi-static and axisymmetric simplifications [5], heat distribution laws, and statistical methods [6]. An analytical solution was also used to obtain the heat generation rate in the semi-infinite space.

In this study, we will apply the developments of the Partial Element Equivalent Circuit (PEEC) method to calculate the magnetic interactions and magnetic flux densities created by excitation coils, taking into account the relative movement of the excitation coil along the three spatial axes and its inclination [7]. We will also use the principle of coupling of the Integro-Differential method. The coupling of the PEEC and FEM methods is applied to simulate eddy currents in thin plates, implementing magnetisation and current effects, and then calculate the integral results among 2D triangular finite elements. A regular mesh of the exciting coil is generated by PEEC method considerations. In this manner, we can benefit from the advantages of both methods (PEEC and FEM), such as reduced computation time, taking into account complex conductors, and considering magnetic materials.



Fig. 1. Example of real application.

II. MODELING PRINCIPLE

In the computation process for induction heating simulation, which geometrical model is presented by Fig. 2. First, the Three-dimensional eddy current distribution is performed in structures having heterogeneous dimensions with the designated initial conditions and constraint conditions under a

given frequency and power. The Joule heat obtained from the eddy current calculation is the input of the heat transfer calculation. It is necessary to frequently re-divide the grid based on the coil position when performing moving induction heating forming simulations, which increase the time of computations and decrease computation efficiency.

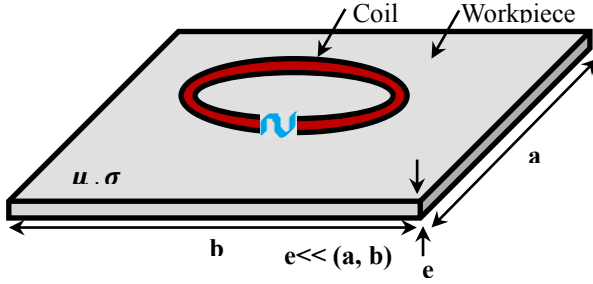


Fig. 2. Geometrical model.

III. PRELIMINARY RESULTS

Fig. 3 shows the comparison between the amplitude of the current density distribution in a massive coil above a conductive magnetic medium, computed with the FEM-PEEC model (Fig.3.a) and Flux3D finite element software (Fig.3.b).

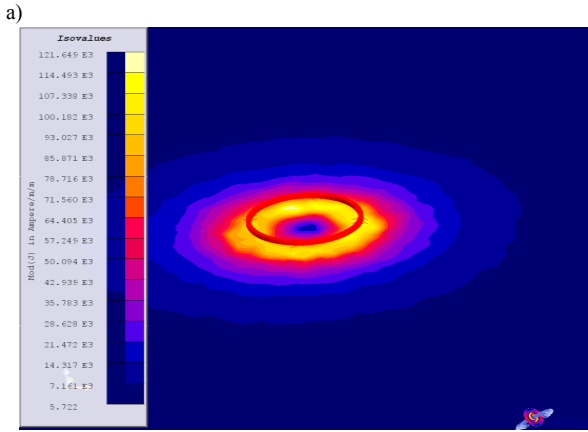
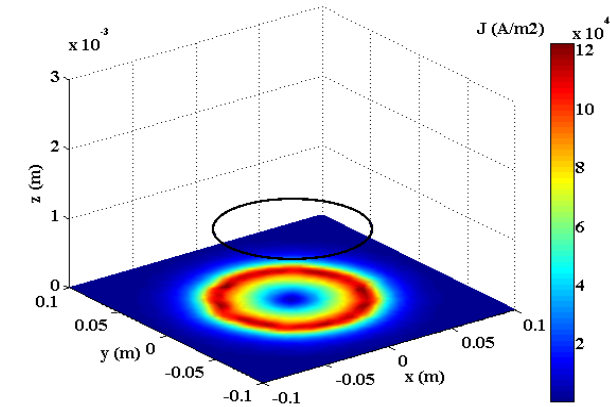


Fig. 3. Eddy current in workpiece computed
a) Calculation by FEM-PEEC method. b) Calculation by FEM method.

The good agreement observed in Figure 3 confirms the accuracy of our model in computing current distributions.

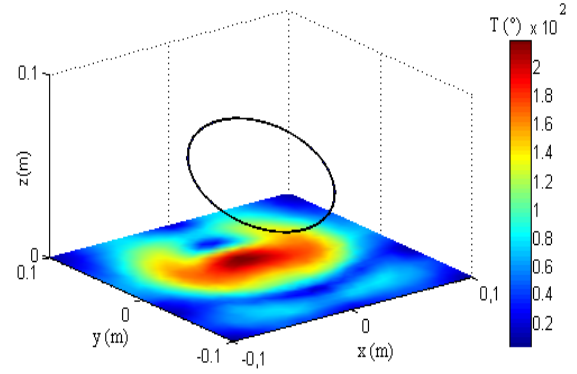


Fig. 4. Temperature computation, incline effect of the excitation coil.

The inclination of the coil impacts the spatial distribution of the electromagnetic field and heat generation, affecting the precision of temperature control in the treated area, as shown Fig.4.

CONCLUSION

In this study, we developed an Integro-Differential formulation for the three-dimensional temperature calculations in structures with heterogeneous dimensions and in the vicinity of ferromagnetic substances. The MEF-PEEC method was successfully applied to a multiphysics numerical model for induction heating. The PEEC method was used to calculate magnetic quantities created by various geometrical shapes of massive coils, particularly the magnetic field considered as a source that generates the eddy currents in the workpiece. Additionally, our approach incorporated various coil inclinations, parameterized by the inclination angle and modeled using Euler transformations.

Our model accurately predicted the distributions of induced current and temperature generation in the heated workpiece using various types of coils, achieving efficient computation times. We validated our approach by comparing results with those obtained using FLUX3D and COMSOL software.

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