Field-circuit Coupled Transient Simulationfor Special Electromagnetic Induction System

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Abstract — **Thispaper simulated the field-circuit coupled transient response with COMSOL multiphysics for one specialelectromagnetic induction system. With the simulation, we obtained the magnetic flux density distribution, the current density of coils, the voltage waveforms of the transmitting coil and the load resistor. We also made a comparison on voltage between the simulation result and experimental result.We did a more in-depth research on the electromagnetic properties of theelectromagnetic induction system.**

Keywords- electromagnetic induction; coupled simulation; finite element

I. INTRODUCTION

Experimental study of electromagnetic induction can date back to the 1820s. Oersted discovered that an electric current creates a magnetic field, and Faraday discovered that changes in magnetic flux create an electric current[1]. These discoveries promote our understanding of electromagnetic induction. Jefimenko thinks in time-dependent systems both fields are simultaneously created by the time-variable electric current. A time-variable electric current creates an electric field. This field exerts a “dragging force” on electric charges located within nearby conductors thus creates induced electric currents in them [2]. Maxwell's electromagnetic theories give us a more profound understanding of electromagnetic induction, and lay the theoretical foundation for the widespread application of electromagnetic induction.

Electromagnetic induction generates eddy currents in the conductor,so the conductor gets hot. This principle can be used to develop the electromagnetic induction heating. Huang etc. did a research on the electromagnetic induction coil design for mold surface heating [3]. Electromagnetic induction can be applied to a detector. Li Hua etc. did a research on electromagnetic induction of electromagnetic tomography [4]. Electromagnetic induction is a very good way of wireless energy transmission. Y. Ota etc. did a research on the “LC booster method” which is a new electromagnetic-induction-based wireless energy transmission system [5].

Electromagnetic induction setting system can be regarded as a special kind of wireless power and signal transmission device relying on electromagnetic induction. Zhang Feng etc. used the electromagnetic induction theory and equivalent circuit method to analyze the energy transmission efficiency and signal transmission characteristics of the system [6]. GuJihui etc. analyzed the structure of a high-frequency near-field electromagnetic induction transmitting device, created a mathematical model for the device and derived the calculating formulas which are able to calculate the magnetic field spatial distribution inside the finite sparse spiral current carrying coils [7]. Huang Xuegong etc. created a finite element model for an electromagnetic induction setting system, did a simulation to calculate the electromagnetic field generated by the transmitting coil and analyze the influences of different materials on the magnetic field [8]. Li Changsheng etc. established an improved accuracy mathematical model that fully took the influence of eddy currents on the electromagnetic induction system into considerationand did a relative simulation to analyze the process of electromagnetic induction setting [9].

As can be seen from their researches, Maxwell’s electromagnetic theories can explain electromagnetic induction system very well, while analytical solutions for such Maxwell’s equations are very difficult to obtain. Computer numerical simulation method provides an effective way to solve Maxwell’s equations for us. Common numerical methods for solving Maxwell equations are the finite element method, the finite difference time domain method, the method of moments, etc. Each of them has its own different scope of application [10]. We also see that when using equivalent circuit method to analyze the induction setting system, some experts ignored the specific structure of the system; when using electromagnetic theory to analyze the induction setting system, some of them didn’t consider the electromagnetic interaction between the transmitting coil and receiving coil, and some others ignored the current distribution in the coil and the field-circuit coupling properties of the system.

In order to learn about the influence of the structure on the magnetic field distribution, the current distribution in the coil and the field-circuit coupling propertiesof the electromagnetic induction setting system, according to the characteristics of the system that has small power size and low signal frequency, this paper selected the computer numerical simulation software COMSOL Multiphysics which is based on finite element method to establish a model for the electromagnetic induction setting system. And we did a field-circuit coupled transient simulation for the system with this model. We did a further research on its electromagnetic characteristics, and explored an integrated optimal design method for the electromagnetic induction setting system.

II. The Quasi-Static Magnetic Principle

The magnetic field in the induction setting system is quasi-static.

Maxwell's equations:

$$\nabla\times H = J + \frac{\partial D}{\partial t} \quad (1)$$

$$\nabla\times E = -\frac{\partial B}{\partial t} \quad (2)$$

$$\nabla\cdot D = \rho \quad (3)$$

$$\nabla\cdot B = 0 \quad (4)$$

In electromagnetic induction setting system, the transmitting and receiving coils are separated by a layer of air. Normally, the air conductivity is zero.Thus, air can be regarded as an ideal medium. In ideal medium, assume the field motivated by the source which is at r is sinusoidal electromagnetic field:

$$E = \mathrm{Re}[E_0 e^{jwt}] \quad (5)$$

So, the field at r' has the following form:

$$E \approx \mathrm{Re}[E_0 e^{jw(t-\frac{R}{v})}] \quad (6)$$

$$R = |r - r'| \quad (7)$$

Where, $e^{-j\frac{wR}{v}}$ is the delayed effect factor. If we want to ignore the delayed effect between the field and source, we should have the factor $e^{-j\frac{wR}{v}} \approx 1$. This is equal to $\frac{wR}{v} = \frac{2\pi R}{\lambda} << 1$ or $R << \lambda$.

This is the limitation that time-varying electromagnetic field can be regarded as quasi-static magnetic field in ideal medium [11]. It means that only if the distance from the source point to the field point is much less than the wavelength of the field, ignoring the displacement current density is reasonable; it also means that if the problem can be solved with a quasi-static method, the size of the system must be much smaller than the wavelength of electromagnetic waves.

In normal electromagnetic inductive setting system, the frequency does not exceed tens of megahertz, the diameters of induction coils do not exceed tens of centimeters, and the distance between coils also does not exceed a few centimeters. If the frequency is 20MHz, for example, the maximum size of the system is much smaller than the wavelength of the electromagnetic wave. Thus, the general problem of normal induction setting system belongs to the quasi-static problem, and can be solved by quasi-static magnetic field method.

Thus, ignoring the displacement current density, equation (1)can be written as follows:

$$\nabla\times H = J \quad (8)$$

In quasi-static magnetic fields, E, B, A and φ still havethe followingrelationships [11]:

$$B = \nabla\times A \quad (9)$$

$$E = -\frac{\partial A}{\partial t} - \nabla\varphi \quad (10)$$

$$\nabla^2 A = -\mu J \quad (11)$$

$$\nabla^2\varphi = -\frac{\rho}{\varepsilon} \quad (12)$$

Thus, if we know the distributions of the current and the charge, we can use these equations to calculate A and φ, and then obtain B and E.

III. Field- Circuit Coupled Simulation for Induction Setting System Based on COMSOL Multiphysics

As mentioned above, the induction setting process belongs to the quasi-static magnetic field category. COMSOL Multiphysics is a finite element simulation software. The AC/DC module of COMSOL Multiphysics is specifically designed to solve quasi-static electromagnetic problems, and it is very suitable for the simulation of induction setting system.

A. Building Model

The structure of the induction setting coils is simple,and the system is symmetrical. Thus, two-dimensional simulation is suitable for induction setting system. In this way, without affecting the accuracy, it can effectively reduce the amount of calculation, improve the reliability of the simulation, and save a lot of time. Two-dimensional geometric model of theelectromagnetic induction setting system is shown in Figure 1. In order to be more realistic, the model includes transmitting and receiving coils, a barrel, a fuse body, a hood and a projectile body.The transmitting coil has two turns, and it is represented by two circles; the receiving coil has four turns, and it is represented by four circles. Transmitting and receiving coils' material is copper, the barrel is glass fiber, the material of the fuze body and projectile body is aluminum, the material of the hood is resin, and the entire system is put in air. The relative properties of each kind of the materials are shown in Table 1. The conductivity of the glass fiber and resin uses anintermediate value of this kind of materials according to some relative information and literature[12].

TABLE I. MATERIAL PROPERTIES.

Material Type	Relative permeability	Relative permittivity	Conductivity (S/m)
air	1	1	0
copper	1	1	5.998×10^{7}
Aluminum	1	1	3.774×10^{7}
Glass fiber	1	5	1.2×10^{-11}
Resin	1	3.8	1.1×10^{-13}

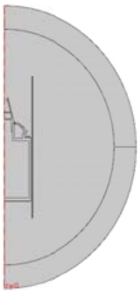

FIGURE I. GEOMETRIC MODEL.

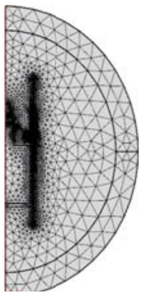

FIGURE II. GRID MODEL.

B. Meshing

In COMSOL Multiphysics, Element Size is used to set element size parameters including maximum element size, minimum element size, maximum element growth rate etc. COMSOL Multiphysics has nine different levels of grid divisions. From extremely coarse to extremely fine, each level corresponds to different mesh parameter settings. This software also comes with a powerful automatic meshing capability. Because we did a two-dimensional simulation, and the model structure is not complicated, so we applied automatic mesh in the model of induction setting system. And the grid model is shown in Figure 2

C. Equivalent Circuit and Incentive

Electromagnetic Induction Setting system contains the transmitting coil and the receiving coil. And it also contains the circuit section. We have already built the model for the coil section. We still need to build the model for the circuit section. The simplified equivalent circuit of the induction setting system is shown in Figure 3. In Figure 3, L1 represents the transmitting coil, L2 represents the receiving coil. R2 represents the equivalent resistor. C2 represents the tuning capacitor. u1represents voltage source with the amplitude 20V and frequency 13.5MHz, providing a sinusoidal excitation signal for the transmitting coil. Since the voltage source can't be directly connected to the coil in COMSOL, a small resistor is connected in the circuit between the source and the coil, in order to ensure the simulation goes smoothly. When the frequency is 13.5MHz, the reactance of the coil is much larger than the resistor's value. Thus the effect of resistor to the coil is negligible.

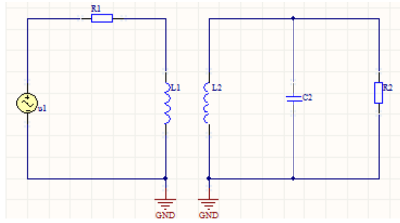

FIGURE III. EQUIVALENT CIRCUIT.

D. Magnetic Field and Circuit Coupling

In this model, the AC/DC module of COMSOLmultiphysics uses "mf" physics field to simulate the coil section, and uses "cir" physics field to simulate the circuit section.In order to achieve the magnetic field and circuit field coupled simulation, we must do some coupling setting between the two physics field. In the "mf" physical field, in Single-Turn Coil property window, set Coil excitation to Circuit (current). In "cir" physical field, firstly, add External IvsU component, and then set its Electric potential to Coil voltage (mf/stcd). The coupling setting between the two fields is completed.

E. Solving

Because we want to simulate the interaction process between the transmitting coil and the receiving coil, we choose the Time Dependent Solver. This simulation is a two fields coupled transient simulation, and the model contains several subjects which are made from different materials. The model is nonlinear in space and time. The amount of calculation is a little large. The solver needs to be robust enough to handle this simulation and runs efficiently. Thus, we setTime Dependent Solver I to Fully Coupled, enable the Direct Solver, set Jacobian update to on every iteration, and set maximum number of iterations to 25 [13]. At last, set time unit to "s" and Times to range (0, 2.0e-9, 6.5e-7).

IV. SIMULATION RESULTS AND ANALYSIS

A. Simulation Results

Figure 4-9 show the results of the simulation. Figure 4 is the two-dimensional magnetic flux density distribution at $t = 2 \times 10^{-8}s$.The magnetic flux density near the coils is significantly greater than the magnetic flux density far from the coils. The distribution trend of magnetic flux density at any other moment issimilartothe trend at $t = 2 \times 10^{-8}s$.It shows that the magnetic flux density generated by the coil decreases rapidly as the distance increases. Figure 5 is the curves of the magnetic flux density at the central axis (r=0), at different moments. Each curve represents a sampling time. The magnetic flux density at the central axis varies with the change of the coordinate Z. Seen from the top to the bottom in the simulation model, i.e., looking from right to left in Figure 5, at Z = 50mm, the magnetic flux density at the central axis decreases rapidly to zero. From Z = 50mm to Z =

-170mm, the magnetic flux density is zero. This part of the axis is surrounded by the fuze body and the projectile body which are made from aluminum. Aluminum is a kind of good conductor. It proves if a confined space is surrounded by a good conductor, the external changing magnetic field will be shielded, and the internal magnetic flux density will be zero.

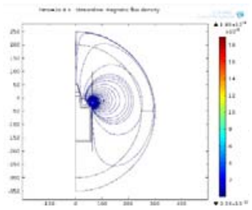

FIGURE IV. MAGNETIC FLUX DENSITY DISTRIBUTION.

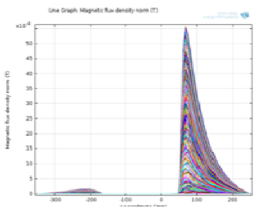

FIGURE V. MAGNETIC FLUX DENSITY AT AXIS.

Figure 6 is the current density distribution of a cross-section of the transmitting coil, and Figure 7 is the current density distribution of a cross-section of the receiving coil. As can be seen from the figures, the current density at the surface of the coil is significantly higher than the current density within the coil. This shows that at the frequency of 13.5MHz, the copper coil current has a strong skin effect, and the current mainly concentrates at the surface of the coil.

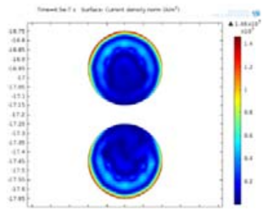

FIGURE VI. CURRENT DENSITY IN TRANSMITTING COIL.

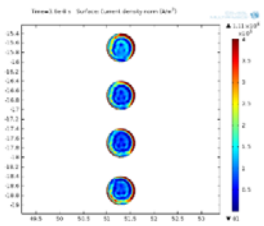

FIGURE VII. CURRENT DENSITY IN RECEIVING COIL.

Figure 8 is the voltage waveform on the transmitting coil changing with time, and Figure 9 is the voltage waveform on the equivalent load resistor R2, obtained by simulation. When adding a sinusoidal alternating voltage of 20V on the transmitting coil, the coil can produce a sinusoidal magnetic field in the surrounding space, motivating the receiving coil to generate an induced electromotive force. By adjusting the value of C2, the amplitude of the voltage on the equivalent resistor R2 can reach about 21V. It indicates that in this structure, by means of electromagnetic induction effect, the receiving coil can effectively feel the change of the magnetic flux generated by the transmitting coil and can generate a sufficient output voltage on R2.

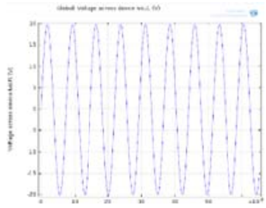

FIGURE VIII. VOLTAGE ON TRANSMITTING COIL.

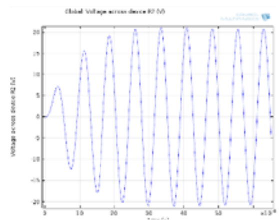

FIGURE IX. SIMULATION VOLTAGE ON R2.

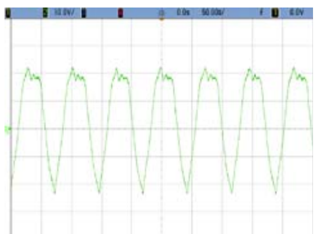

FIGURE X. EXPERIMENTAL VOLTAGE ON R2.

B. *Comparison to Experiments*

Make a real model with the same size. Use an E-class power amplifier to supply a 20V, 13.5MHz sinusoidal voltage to the transmitting coil. By tuning, apply an oscilloscope to measure the voltage on the R2. The result is shown in the Figure 10. Comparing Figure 9 with Figure 10, find that the measured peak value by the experiment is very similar to the calculated peak value by the simulation. The error between the simulation result and the experiment result is very small.

V. CONCLUSIONS

This paper used COMSOL Multiphysics to do a field-circuit coupled transient simulation for the electromagnetic induction setting system. We obtained the magnetic flux density distribution of the system and learned the influences of the aluminum projectile and fuze body on the magnetic flux density distribution. We obtained the current density in the cross-section of the transmitting coil and the receiving coil and found the current skin effect is obviously strong. We also obtained the voltage waveforms on the transmitting coil and on the load resistance R2 and this proved the system is able to effectively transfer energy from the transmitting coil to the receiving coil wirelessly. This paper also made a comparison between the simulation result and the experiment result, found the relative error between the simulation value and the measured value was less than 10% and this indicated that the simulation is accurate. The field - circuit coupled transient simulation for the induction setting system studied the electromagnetic characteristics of the system, built a bridge from the field to the circuit for the research on the system. This kind of simulation could give good references and recommendations for selecting materials, the circuit and structural design and was meaningful for the integrated optimization design of the electromagnetic induction setting system.

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