A Numerical Method for Analyzing Electromagnetic Properties of a Moving Ferromagnet with One-side Conducting Border

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A novel numerical method, referred to as PA-PITD (parameter approximation precise integration time domain method) wherein parameter approximation technique and PI technique are both employed is proposed to model the electromagnetic properties of the moving ferromagnetic object. The proposed algorithm is validated in the context of a practical simulation, a moving ferromagnet with a conducting border on one side. Moreover, several valuable phenomena are first observed with the PA-PITD-calculated results.

Index Terms—Electromagnetic fields, moving object, nonlinearity, numerical methods.

I. INTRODUCTION

THE movement of an object makes a notable impact on its electromagnetic properties, especially in the high-speed case. The impact is weak when the speed of an object is relatively low. However, if the medium is ferromagnetic, low speed also affect the interaction of the moving object with the electromagnetic field significantly. Considering this fact, a novel numerical method designated as PA-PITD method is proposed in this paper and applied to the case in which Ferromagnet is present. In the PA-PITD method, Yee-grid is employed to arrange the electric\magnetic field components. The PI technique is utilized to solve the discretized form of the governing equations in each cell. Particularly, parameter approximation scheme is developed in the cells where the boundaries of the moving ferromagnetic medium reside. In those mixed-medium cells, the effective parameters are approximated via a weighted averaging procedure. Moreover, since the coefficient matrix in the PA-PITD is time-variant, an effective constant coefficient matrix in a single time interval is constructed. Results show that both the large permeability and the nonlinearity of the ferromagnet are responsible for the distinct interaction of the moving ferromagnetic medium with the electromagnetic field. In addition, the PA-PITD method is favorable in the analysis of the evolution of the fields around the moving ferromagnetic medium.

II. COMPUTATIONAL MODEL

The physic model considered in this paper is shown in Fig. 1. This configuration in Fig. 1 is usually encountered in the aeromagnetic area and some applications in military. The combed boundary is perfect conductor. Four cases are discussed. Case I: The input is the time-harmonic excitation of 2000 Hz. The object is constantly moving with the speed of 10000m/s; Case II: The input is the time-harmonic excitation of 2000 Hz. The object is in translational motion with acceleration $2.67{\times}10^7$ m/s²; Case III: The input is Gaussian excitation. The object is constantly moving with the speed of 10000m/s; Case IV: The input is Gaussian excitation. The object is in translational motion with acceleration $2.67{\times}10^7$m/s². The time step size is 20μs and the simulation time duration is 0.0075s. The displacement of the ferromagnet
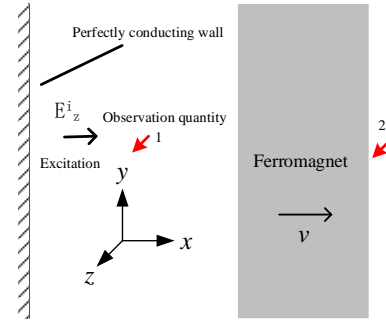

Fig. 1 Moving ferromagnet with one-side conducting border

in the four cases are the same under such settings

In our research, the excitation is a point-wise H source with unity amplitude. Absorbing boundary condition is imposed on the right boundary and perfectly conducting condition on the left boundary. Two observation points are settled, highlighted by the red color in Fig. 1. One can get the knowledge of the impact of the motion on the electromagnetic field with the aid of the waveforms at the observation points.

III. PARAMETER APPROXIMATION SCHEME

The Yee-cell around the boundaries includes both the host medium and the moving medium. The scheme to determine the parameters in the cells partially filled with moving ferromagnetic medium is elaborated here. Suppose that ψ denotes the effective constitutive parameter (permittivity, permeability...) of the cell, ψ_h denotes that of the host medium and ψ_m the moving medium, respectively. f_{frac} is defined as the ratio of the area occupied by the moving medium to the area of the whole cell. Then ψ is expressed as

$$\psi = \left(1 - f_{frac}\right) \cdot \psi_h + f_{frac} \cdot \psi_m \qquad (1)$$

IV. PRECISE INTEGRATION TIME DOMAIN

The PITD method is a common tool in analyzing electromagnetic wave problem [1]. In the PITD method, the Yee-grid inherited from the finite difference time domain (FDTD) method is employed to arrange the discrete electromagnetic field components in space. The electric

components and the magnetic components appear alternatively by half spatial increment in each direction. On the contrary, the electric components and the magnetic components are sampled at the same series of time points. Suppose that the object is moving along the *x*-axis in Cartesian coordinate system. When the TEM wave is considered(shown in Fig. 1) in 2D, the modified discretized formulations of the Maxwell curl equations in the cells, in which the moving material locates, are given as a set of ordinary differential equations (ODEs) for the TEM mode.

$$\varepsilon \frac{\partial E_y(i)}{\partial t} + \frac{\partial \varepsilon}{\partial t} E_y = \frac{H_z(i-0.5) - H_z(i+0.5)}{\Delta x} \quad (2)$$

$$\mu \frac{\partial H_z(i+0.5, j+0.5)}{\partial t} + \frac{\partial \mu}{\partial t} H_z = -\frac{E_y(i+1) - E_y(i)}{\Delta x} \quad (3)$$

Note that the time partial differential terms of the permittivity and the permeability are introduced due to the movement. These two terms can be expressed explicitly with the moving speed.

V. PIECE-WISE CONSTANT COEFFICIENT MATRIX

The overall coefficient matrix **M** is varied with time under the condition that the target is moving. The formulation of the conventional PITD method has to be modified. Since **M** becomes time-variant, (2)~(3) are written in a general form as

$$\frac{d\mathbf{X}}{dt} = \mathbf{M}(t)\mathbf{X} + \mathbf{f}(t) \quad (4)$$

X consists of all the electromagnetic field components. The analytical solution of the set of ODEs is, in most cases, impossibly obtained. Fortunately, an effective time-constant substitution of time-variant **M**(*t*) can be constructed provided that the time step size Δt is sufficiently small. The coefficient matrices designated as $\mathbf{M_s}$, $\mathbf{M_e}$, and $\mathbf{M_m}$ at the starting point, the ending point, and the middle point, respectively, are linearly combined to construct the effective matrix **M** in a single time interval. The middle time point is totally included in the time interval, both the starting and the ending time points are the joint points for two consecutive time intervals and equally shared by the two consecutive time intervals. As a result, the effective constant matrix **M** can be properly expressed as

$$\mathbf{M} = 0.25\mathbf{M}_s + 0.5\mathbf{M}_m + 0.25\mathbf{M}_e \quad (5)$$

It is apparent that **M** over all time becomes piece-wise constant, then the PITD method can be used to solve (4).

VI. NUMERICAL RESULTS

In this section, the results of case I, case II, case III, and case IV are presented to test our algorithm. The observation quantity is the magnetic intensity component. In our research, (6) is adopted to indicate the relation between the magnetic flux density and the magnetic intensity inside the ferromagnet.

$$\begin{cases} \mathbf{B} = 1000\mu_0\mathbf{H} & \mathbf{H} < \mathbf{H}_{thres} \\ \mathbf{B} = 1.05\mu_0\mathbf{H} & \mathbf{H} > \mathbf{H}_{thres} \end{cases} \quad (6)$$

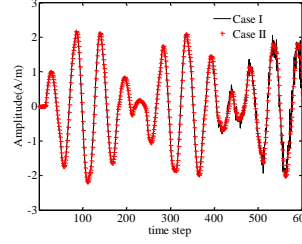$\mathbf{H}_{thres}$ is the saturation point of the ferromagnet, μ_0 is the permeability of vacuum.

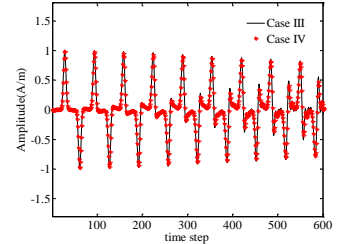Fig. 2(a) Waveform of H_z at point 1
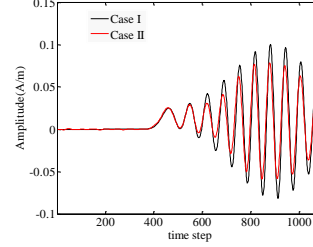

Fig. 2(b) Waveform of H_z at point 1

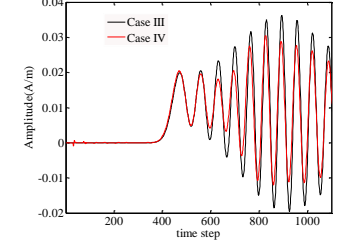Fig. 2(a) Waveform of H_z at point 2

Fig. 2(b) Waveform of H_z at point 2

VII. SUMMARY AND CONCLUSION

The PA-PITD method is developed to the application involving ferromagnetic and the conducting wall, a structure usually encountered in the field of the military applications and the geoelectromagnetic field. Numerical results indicate that the anticipated Doppler frequency shift [2] is observed for the time-harmonic excitation, and the length of pulse is stretched and the amplitude is mitigated for the Gaussian excitation [3].These can be evidence that the proposed method is favorable to the problem considered. Little fraction of energy can pass through the moving ferromagnet especially for the accelerated moving case since the electromagnet field is required to provide extra energy to the ferromagnet for the acceleration. For Gaussian excitation case, moving ferromagnet functions like a filter, only low-frequency components can pass through among which the magnitude of 1560Hz is the largest. A quite interesting finding is that an intrinsic frequency component of about 1560 Hz exists in all four cases at both observation points. It is surmised that this phenomenon is related to the nonlinearity of the ferromagnet and is free from the motion of the ferromagnet at a relatively low speed. Although only TEM mode is considered here, the extension to TE mode, TM mode at oblique incidence in 2-dimensional and 3-dimensional is straight forward if only the coefficient matrix is obtained.

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