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授　与　学　位	博士（工学）
学位授与年月日	平成２２年９月８日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）電気・通信工学専攻
学位論文題目	Study on Numerical Analysis of Electromagnetic Field Based on CIP Method（CIP 法を用いた電磁界の数値解析法に関する研究）
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論文内容要旨

Analysis of electromagnetic problems including antennas, specific absorption rate (SAR) calculation for biological electromagnetic effect between antenna and biological body, design of printed antennas on finite dielectric substrates, microwave devices, monolithic microwave integrated circuits, communications, radars and imaging, and so on, requires numerical methods, which become extremely powerful with today's computer technology and intelligent parallel processing approaches. Two popular numerical techniques for these kinds of problems are based on either integral equations or partial differential equations. Integral equations are often numerically solved with the method of moments (MoM), which is one of the most widely used. The finite difference time domain (FDTD) technique is also one of the most popular numerical method for solution of partial differential equations appeared in EM area. However, no single method, either analytic or numerical, is best suited for handling all possible cases in these problems; instead, a combination of methods is required to attain greatest flexibility and efficiency. Therefore, the trend is definitely toward "hybridization".

In this thesis, a numerical approach using the constrained interpolation profile (CIP) method, which was first proposed by Yabe et al. in 1985 in the field of computational fluid dynamics, is applied to three-dimensional electromagnetic analysis of plane wave scattering by perfectly conducting and dielectric objects. In addition, the combination of the CIP method with the FDTD method is proposed to analyze the antenna problems. The FDTD method suffers from numerical dispersion or anisotropy, i.e. numerical propagation velocity of electromagnetic wave depends on cell size, time step size, and direction of propagation. This anisotropy causes an accumulative phase error and restricts the analysis solution to the Rayleigh or resonance region where electrical length is in the order of a few wavelengths. The CIP method

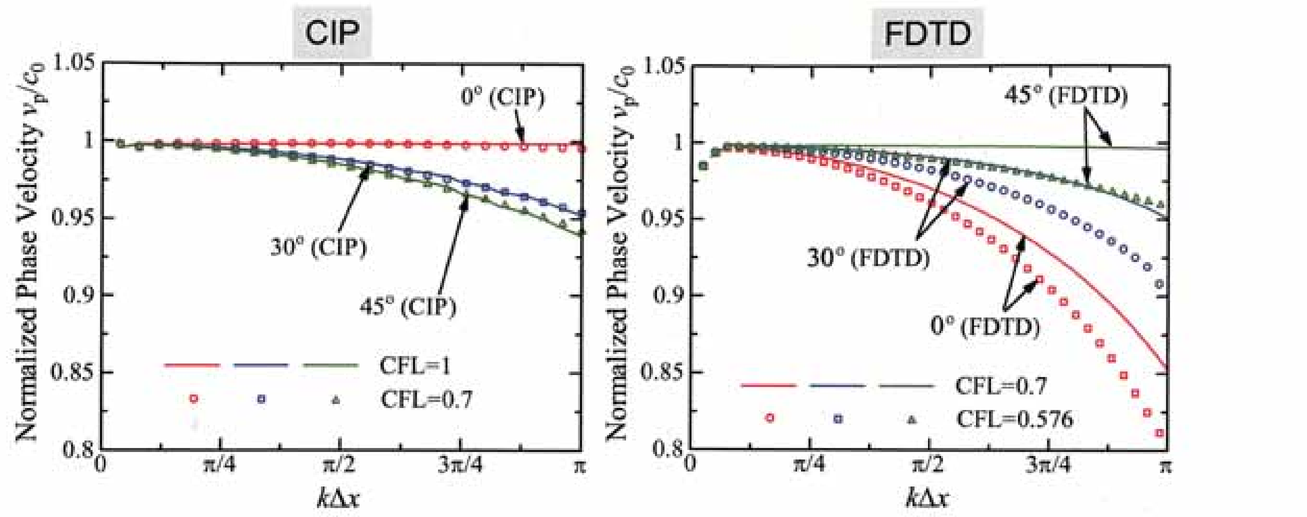

Fig. 1 Phase characteristics of the CIP and FDTD method.

has better phase characteristics than the FDTD method so that it is expected that the phase error or dispersion effect is reduced by using the CIP method in the propagation region of electromagnetic wave.

Firstly, we applied the CIP method to the Maxwell's equation by using the characteristic method, and then update equations for electric and magnetic fields are derived. Next, the results of 2d numerical analysis for stability and accuracy of the CIP method showed us that the amplitude of electromagnetic waves simulated by the CIP method decreases gradually every time step except in the case of CFL = 1 where amplitude of electromagnetic field analyzed using the CIP method oscillates around a constant value without decrease. Consequently, CFL number must be set to unity to give an accurate result in the CIP method. This result reflects the analysis in the successive part of the thesis in which we set CFL to unity. Besides that, the CIP method shows better phase characteristics compared to conventional Yee's FDTD method as shown in Fig. 1. Phase errors in the CIP method is about half of that in the FDTD method for the case of identical cell size.

Then, the CIP method was applied to three-dimensional scattering problems in electromagnetics. Before PEC or a dielectric objects can be modeled, the boundary condition for each material is defined and formulated for the CIP method. Update equations for PEC, lossless dielectric interfaces are derived. Additionally, computation algorithm for lossy dielectric object is proposed and verified by the results. From the analysis results, it was shown that

1. The boundary condition for PEC interface is validated by numerical results of scattering cross sections of a PEC sphere. The fact that the outermost boundary in the CIP method behaves like the first-order Mur absorbing boundary condition in the FDTD method was confirmed by the numerical results.

2. For the lossless dielectric case, the phases of scattering coefficient of dielectric sphere obtained by the CIP method are more accurate than that of the FDTD method. The numerical results show the

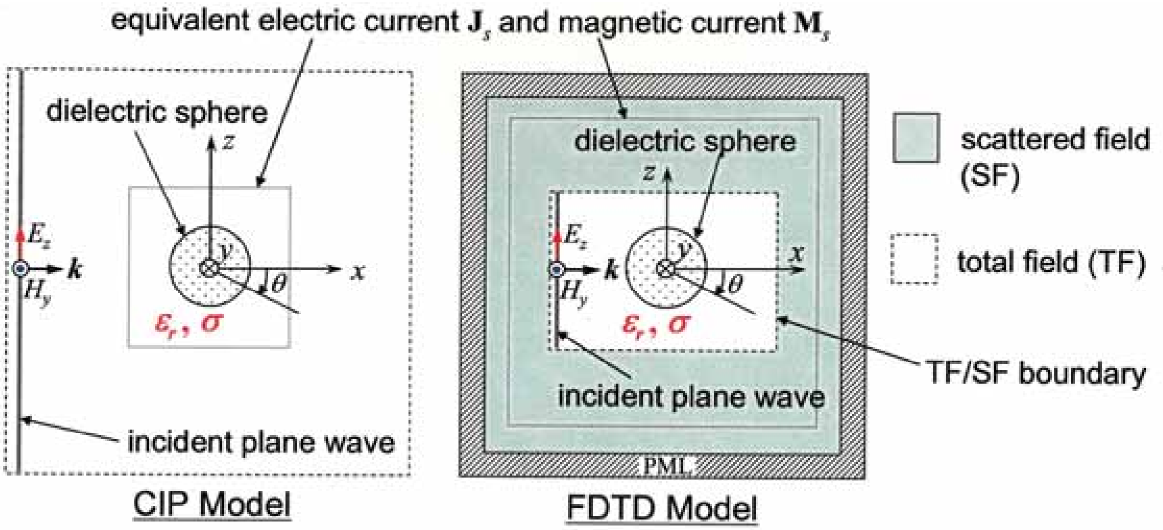

Fig. 2 Analysis model for the CIP and FDTD method.

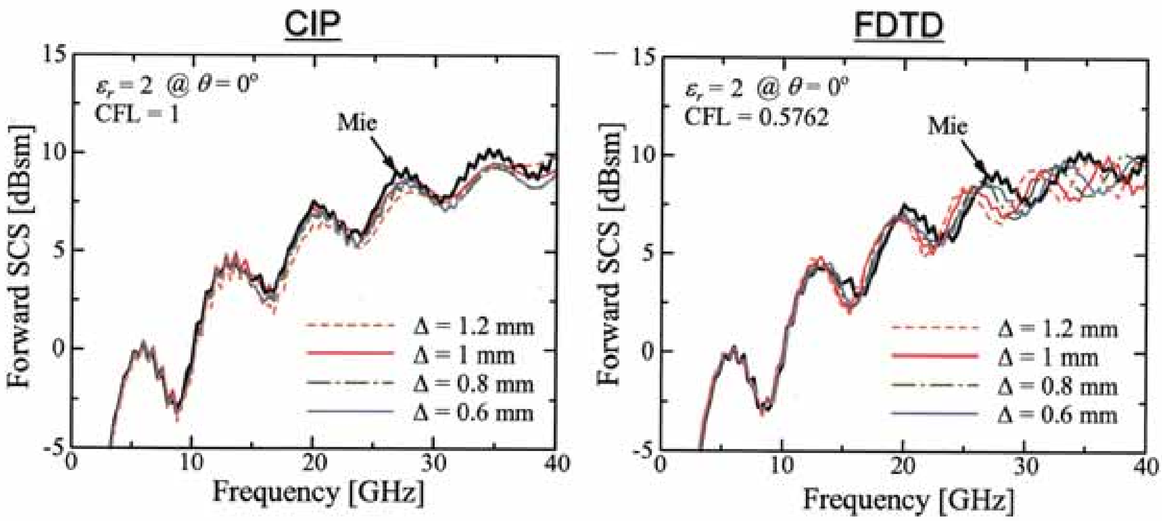

Fig. 3 Forward scattering cross section obtained by the CIP and FDTD method.

correspondence between the analytical results obtained by Mie's series and the results obtained by the CIP method. The resonant peaks of forward scattering cross section (SCS) obtained by the CIP method do not change with respect to the cell size while the forward SCSs are shifted to the lower frequency when the cell size is large in the FDTD method. These forward SCSs showed the superiority of the CIP method over the FDTD method in the scattering problems. The analysis model and analysis results are shown in Fig. 2 and Fig. 3, respectively, where Δ is the spatial discretization in each axis.

3. For the lossy dielectric case, the accuracy of the scattering cross section computed by using the CIP method is better than that of the FDTD method. Additionally, using the property that electric and magnetic fields locate at the same location in the CIP method, the calculation of radiated power can be done straightforwardly while in the FDTD method, an averaging method must be used to determined electric and magnetic fields at the same place. The total scattering cross section obtained by the CIP method shows a

good agreement with the Mie's analytic result while that of FDTD method presents some discrepancy in the analysis results.

In the last part of this thesis, we proposed a new hybrid method called CIP-FDTD hybrid method to solve radiation problems in electromagnetics. Firstly, we proposed a boundary between the region calculated by using the FDTD method (so-called FDTD region) and the region calculated by using the CIP method (so-called CIP region) and showed a valid algorithm for the boundary. Next, the phase characteristics of the CIP-FDTD method was characterized in 2d analysis space by computing the phase velocity in each propagation direction and compared them with the results. We found that the phase error is almost the same with the case of the CIP method in whole region. Therefore, by combining the FDTD region and CIP region together, we can reduce the propagation phase error occurred by dispersion inherited in the FDTD method because most of the propagation region is now the CIP region which have much smaller dispersion. The validity of the proposed boundary was confirmed by the reflection and transmission coefficients. Finally, we analyzed the antenna model to show the possibility of the CIP-FDTD hybrid method for the analysis of radiation problems in electromagnetics.

論文審査結果の要旨

無線通信をはじめとする電波利用分野の高度化に伴って，複雑なアンテナの設計や伝搬特性の解明のための電磁界解析技術が重要になっている。従来，モーメント法や時間領域差分（Finite Difference Time Domain: FDTD）法，有限要素法などの数値解析手法が用いられてきたが，それぞれ固有の欠点を有しており，他の電磁界の数値解析法を開拓する必要がある。著者は流体力学の分野で開発された拘束条件付き形状補間（Constrained Interpolation Profile: CIP）法を3次元の電磁界解析に拡張し，その有効性や精度について研究を行った。本論文はこの成果をまとめたもので，全編5章よりなる。

第1章は緒言であり，研究の背景について述べている。

第2章では，CIP法をマクスウェル方程式に適用するための定式化を行っている。また，正弦状平面波の伝搬問題にCIP法を適用し，その解の安定性について論じ，安定条件を明らかにしている。さらに，位相誤差について検討し，CIP法の誤差がFDTD法に比べて小さいことを示している。

第3章では，導体及び誘電体の散乱問題にCIP法を適用している。まず，完全導体表面及び誘電体表面の境界条件をCIP法に組み入れる手法を提案し，完全導体球及び誘電体球の散乱問題に適用して厳密解と比較することにより，これらの問題にCIP法を適用可能であることを示している。また，CIP法は吸収境界条件を組みいれなくてもFDTD法におけるMurの1次吸収境界条件と同等の吸収境界を実現できることを示している。さらに，損失のある誘電体に対する計算アルゴリズムを提案し，損失性誘電体球の散乱問題を解析している。これらの解析を通じて，CIP法の位相誤差がFDTD法よりも小さいことを示すと共に，CIP法の計算に必要なメモリと計算時間を明らかにしている。これらの結果はCIP法を電磁界解析に適用する際の指針となるものであり，有用な成果である。

第4章では，CIP-FDTDハイブリッド法について述べている。線状アンテナの解析にはCIP法を適用できないことから，線状アンテナ周辺の空間にFDTD法を，また電磁波が伝搬する空間にCIP法を適用するハイブリッド法を提案し，FDTD領域とCIP領域の電磁界の接続法を示している。また，CIP-FDTDハイブリッド法の位相誤差がFDTD法に比べて優れていることを示している。この手法は線状アンテナを含むアンテナ及び電波伝搬の解析に有用な手法である。

第5章は結論である。

以上要するに本論文は，CIP法が電磁界の数値解析に適用可能であることを示し，また位相誤差が小さいことなど，CIP法の特徴を明らかにすると共に，線状アンテナにも適用できるハイブリッド法を提案したもので，電磁波工学ならびに電気・通信工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。