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Fast Analysis of Local Current Distribution for Electromagnetic Scattering Problems of Electrically Large Objects

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ABSTRACT To improve computational efficiency of obtaining local induced current distribution under multiple incidents angles when electromagnetic scattering problems of electrically large objects are considered, a novel method is proposed to form small-scale impedance matrix and reduce number of repeated calculation for different incident angles, which is implemented by following three steps. Firstly, an undetermined matrix equation including multiple incident angles is constructed by interrelating part field nodes and all source nodes on object surface. Secondly, the undetermined matrix equation is transformed into a form that conforms to the compressive sensing (CS) framework, which is solved by reconstructed algorithm to obtain approximate induced currents of all source nodes under a wide incident angle range. Finally, exact wide-angle currents of a given node are obtained by calculating total magnetic field, and neighborhood wide-angle currents of the given node can be expanded by choosing appropriate technology in different boundary conditions. Numerical results of electrically large objects shown the efficiency of the proposed method.

INDEX TERMS Electromagnetic scattering, compressive sensing, local current distribution, electrically large object, multiple incident angles.

I. INTRODUCTION

Local electromagnetic scattering of electrically large object play important roles in estimating strong scattering points of targets [1], analyzing partial geometry modification problems [2], [3], and arranging antennas in platforms etc. Method of moment(MOM) is common numerical algorithm in solving electromagnetic scattering problems, which can obtain high computational accuracy by constructing and solving full-rank matrix equations, however the resulted computational complexity is huge especially for electrically large targets [4], [5]. Based on MOM, many fast algorithms have been developed for improving the computational efficiency, such as fast multipole method (FMM) [6], multilevel fast multipole method (MLFMM) [7], adaptive integral method(AIM) [8], and wavelet transform method [9].

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For local electromagnetic scattering, above methods must interrelate global field nodes and the source nodes, and many redundant coupling points are also included. To tackle the problem, Y. S. Xu proposed discretized boundary equation (DBE) method [10], which can obtain independent current at any interesting node on the object surface with a matrix of smaller order than that in the MoM. Subsequently, asymptotic waveform evaluation (AWE) was employed as a spatial sweep technique to avoid repeating calculations point-by-point for local electromagnetic scattering [11], and iterative OS-DBE (IT-OS-DBE) was proposed to further reduce the number of repeated calculations for smaller order matrix equation [12].

For electromagnetic problems with multiple incident angle excitations, there are some challenges to DBE method. Actually, DBE have to repeat calculate currents under every incident angles, meanwhile, the so-called generalized inverse [13] is employed to solve matrix equation will result into cost expensive for computing resources, which limited the development of DBE method and its application.

Recently, compressive sensing (CS) [14] has been successfully introduced to computational electromagnetics for improving computing efficiency. On the one hand, a special excitation source was proposed to reduce the number of calculations significantly for monostatic electromagnetic scattering over a wide incident angle [15]–[17]. On the other hand, an undetermined equation method was construct under CS framework [18]–[20], which forms a small scale impedance matrix equation and proposed recovery algorithm instead of traditional iteration methods, so that the computational efficiency of matrix equation is improved.

In this paper, a novel method based on CS is proposed to calculate local induced current distribution as electromagnetic scattering problems over a wide incident angle range are analyzed. It is worth noting that the proposed method not only can obtain independent current at any local interesting nodes by constructing smaller undetermined matrix equation, but also reduce the number of calculations greatly at multiple incident angles. Especially, the generalized inverse of the matrix can be avoided by application of reconstructed algorithms in CS [21].

II. THEORY AND FORMULATIONS

A. CONSTRUCTING AN UNDETERMINED MODEL UNDER MULTIPLE INCIDENT ANGLES

For local electromagnetic scattering problems, combined field integral equation(CFIE) can be discretized as a undetermined equation as

$$\mathbf{Z}_{M\times N}\mathbf{I}_{N\times 1} = \mathbf{V}_{M\times 1} \quad (M \ll N) \tag{1}$$

in which $\mathbf{V}_{M\times 1}$ is the incident field excitation, $\mathbf{I}_{N\times 1}$ is the unknown current coefficients, and $\mathbf{Z}_{M\times N}$ is impedance matrix. As shown in Fig.1, M is the number of excitation field nodes distributed arbitrarily on the surface of object, and $N(M \ll N)$ is the number of induced current source nodes distributed on the surface of object.

As the excitation of multiple incident angles is considered, equation(1) can be rewritten as a matrix form as below

$$\mathbf{Z}_{M\times N}\mathbf{I}_{N\times n}(\theta) = \mathbf{V}_{M\times n}(\theta) \quad (M \ll N) \tag{2}$$

where

$$\mathbf{I}_{N\times n}(\theta) = \begin{pmatrix} I_{11}(\theta_1) & I_{12}(\theta_2) & \cdots & I_{1n}(\theta_n) \\ I_{21}(\theta_1) & I_{22}(\theta_2) & \cdots & I_{2n}(\theta_n) \\ & & \vdots & \\ I_{N1}(\theta_1) & I_{N2}(\theta_2) & \cdots & I_{Nn}(\theta_n) \end{pmatrix}_{N\times n}$$

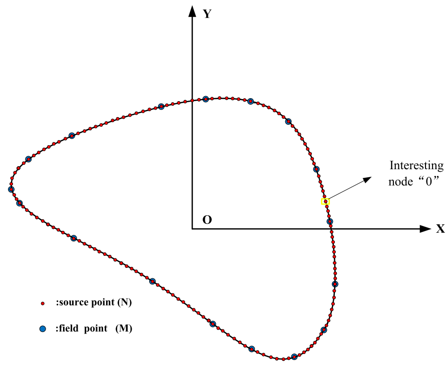


FIGURE 1. Distribution of M field nodes and N source nodes on two-dimensional surface of arbitrary object.

$$\mathbf{V}_{N\times n}(\theta) = \begin{pmatrix} V_{11}(\theta_1) & V_{12}(\theta_2) & \cdots & V_{1n}(\theta_n) \\ V_{21}(\theta_1) & V_{22}(\theta_2) & \cdots & V_{2n}(\theta_n) \\ & & \vdots & \\ V_{M1}(\theta_1) & V_{M2}(\theta_2) & \cdots & V_{Mn}(\theta_n) \end{pmatrix}_{M\times n}$$

in which θ denote incident angle,n is the number of incident angles, in other words, θ is discretized into $\theta_1, \theta_2, \ldots, \theta_n$.

B. SOLVING THE UNDETERMINED EQUATION BY CS SOLVER

In this paper, we use CS solver instead of generalized inverse to solve underdetermined equations (2).

Inspired by framework of CS theory, two orthogonal matrices $\mathbf{\Psi}^1_{N\times N}$ and $\mathbf{\Psi}^2_{n\times n}$ can be employed to thin columns and rows of induced current coefficients $\mathbf{I}_{N\times n}$, respectively, as follows.

$$\mathbf{\Psi}^1_{N\times N}\mathbf{I}_{N\times n}\mathbf{\Psi}^2_{n\times n} = \boldsymbol{\alpha}_{N\times n} \tag{3}$$

$$\mathbf{I}_{N\times n} = (\mathbf{\Psi}^1_{N\times N})^{\mathrm{T}}\boldsymbol{\alpha}_{N\times n}(\mathbf{\Psi}^2_{n\times n})^{\mathrm{T}} \tag{4}$$

Substituting equation (3)(4) into equation (2)

$$\mathbf{Z}_{M\times N}(\mathbf{\Psi}^1_{N\times N})^{\mathrm{T}}\boldsymbol{\alpha}_{N\times n}(\mathbf{\Psi}^2_{n\times n})^{\mathrm{T}} = \mathbf{V}_{M\times n}(\theta) \tag{5}$$

Consider the excitation of multiple incident angles, a new incident source [15] can be implanted into equation(5) as

$$\mathbf{Z}^{CS}_{M\times N}\mathbf{S}_{N\times m} = \mathbf{V}^{CS}_{M\times m} \quad (M \ll N, m \ll n) \tag{6}$$

in which

$$\mathbf{Z}^{CS}_{M\times N} = \mathbf{Z}_{M\times N}(\mathbf{\Psi}^1_{N\times N})^{\mathrm{T}} \tag{7}$$

$$\mathbf{S}_{N\times m} = \boldsymbol{\alpha}_{N\times n}(\mathbf{\Psi}^2_{n\times n})^{\mathrm{T}}\mathbf{\Phi}_{n\times m} \tag{8}$$

$$\mathbf{V}^{CS}_{M\times m} = \mathbf{V}_{M\times n}(\theta)\mathbf{\Phi}_{n\times m} \tag{9}$$

and $\mathbf{\Phi}_{n\times m}$ is a Gaussian random matrix.

From the point of view of CS, $\mathbf{Z}^{CS}_{M\times N}$ can be seen as measurement matrix that satisfies the RIP (Restricted Isometry Property) due to the Toeplitz property of impedance matrix [19], so the known $\mathbf{V}^{CS}_{M\times m}$ are measurements of the sparse vector $\mathbf{S}_{N\times m}$. Take into the sparsity of unknown $\mathbf{S}_{N\times m}$, from undetermined equation (6), one can obtain $\hat{\mathbf{S}}_{N\times m}$ by solving L-norm optimization problem:

$$\hat{\mathbf{S}}_{N\times m} = \arg\min ||\mathbf{S}_{N\times m}||_L \quad s.t.\ \mathbf{Z}^{CS}_{M\times N}\mathbf{S}_{N\times m} = \mathbf{V}^{CS}_{M\times m} \tag{10}$$

In order to reconstruct $\boldsymbol{\alpha}_{N\times n}$,we conjugate the two sides of the equation(8) as

$$(\boldsymbol{\Phi}^{\mathrm{T}})_{m\times n}\boldsymbol{\Psi}^2_{n\times n}(\boldsymbol{\alpha}^{\mathrm{T}})_{n\times N} = (\hat{\mathbf{S}}^{\mathrm{T}})_{m\times N} \tag{11}$$

Similarly to the underdetermined equation (6), $((\boldsymbol{\Phi}^{\mathrm{T}})_{m\times n}\boldsymbol{\Psi}^2_{n\times n})$ can be used as measurement matrix, the known $(\hat{\mathbf{S}}^{\mathrm{T}})_{m\times N}$ can be recognized as measurements of the unknown sparse vector $(\boldsymbol{\alpha}^{\mathrm{T}})_{n\times N}$, and $(\hat{\boldsymbol{\alpha}}^{\mathrm{T}})_{n\times N}$ can be obtained by solving L-norm optimization problem as

$$(\hat{\boldsymbol{\alpha}}^{\mathrm{T}})_{n\times N} = \arg\min ||(\boldsymbol{\alpha}^{\mathrm{T}})_{n\times N}||_L \quad s.t.\ \boldsymbol{\Phi}^{\mathrm{T}}_{m\times n}\boldsymbol{\Psi}^2_{n\times n}(\boldsymbol{\alpha}^{\mathrm{T}})_{n\times N} = (\hat{\mathbf{S}}^{\mathrm{T}})_{m\times N} \tag{12}$$

In this paper, OMP(Orthogonal Matching Pursuit) is employed to perform (10) (12) optimization problems, and the final calculation $\tilde{\mathbf{I}}_{N\times n}$ is obtained by

$$\tilde{\mathbf{I}}_{N\times n} = (\boldsymbol{\Psi}^1_{N\times N})^{\mathrm{T}}\hat{\boldsymbol{\alpha}}_{N\times n}(\boldsymbol{\Psi}^2_{n\times n})^{\mathrm{T}} \tag{13}$$

C. OBTAINING LOCAL EXACT SOLUTION

In order to improve accuracy of independent current at given node "0" on PEC (Perfect Electrical Conducting) object surface, the scattering magnetic field at the node "0" $\mathbf{H}^{0s}_{1\times n}(\theta)$ can be obtained by

$$\mathbf{H}^{0s}_{1\times n}(\theta) = -\frac{1}{4}j\mathbf{d}^0_{1\times N}\tilde{\mathbf{I}}_{N\times n} \tag{14}$$

where

$$\mathbf{d}^0_{1\times N} = \int_{cN} \frac{\partial H_0^{(2)}(k\left|\vec{\rho}-\vec{\rho}'\right|)}{\partial n}dl' \Bigg|_{\vec{\rho}=\vec{\rho}_0} \tag{15}$$

in which ΔcN denote global region, and $H_0^{(2)}$ is the Hankel function of the second kind of order zero.

According to the boundary condition of PEC, the exact current density at node "0" under multi-angle incidence can be determined by

$$\mathbf{J}^0_{1\times n}(\theta) = \mathbf{n}\times(\mathbf{H}^{0i}_{1\times n}(\theta) + \mathbf{H}^{0s}_{1\times n}(\theta)) \tag{16}$$

in which $\mathbf{H}^{0i}_{1\times n}(\theta)$ is known as the multi-angle incident magnetic field at node "0", and $\mathbf{n}$ is outer normal direction of object surface.

For the solution of local interest region, AWE method can be used to expand the node "0" if its neighborhood surface is smooth [11], otherwise, the exact solution at arbitrary node on the object surface can be obtained by changing the position of node "0".

D. COMPUTATIONAL COMPLEXITY ANALYSIS

Compared with the traditional DBE method, the proposed method has the advantage of lower complexity to solve the underdetermined equation under multi-angle incidence, including L-norm optimization problem is solved by OMP twice, whose computational complexity is $O(p_1MNm + p_2mNn)$, where p_1 and p_2 denote iteration steps in two times OMP, respectively. The computational complexity of DBE method is $O(nMN^2)$ since generalized inverse solution for the underdetermined matrix equations. Combine the above two aspects, decrement ratio in computational complexity of the proposed method can be evaluated as

$$\eta = \frac{p_1MNm + p_2mNn}{nMN^2} = \frac{p_1m}{nN} + \frac{p_2m}{MN} \tag{17}$$

where $p1 \ll M \ll N$, $m \ll n$, and $p_2 \ll M$, $m \ll N$.

III. RESULT AND DISCUSSION

To verify the efficiency of the proposed method, local scattering of various electrically large objects are simulated in an Intel core i7 personal computer (CPU@2.4GHz, RAM:8GHz).All objects are irradiated by TM plane waves, whose incident angle is divided into 360 directions ($n = 360$) with 1° increment from 1° to 360°. In this paper, fast Fourier transform(FFT) basis are selected as two orthogonal matrices ($\boldsymbol{\Psi}^1_{N\times N}$ and $\boldsymbol{\Psi}^2_{n\times n}$) in CS solver, and the computational error is described by relative root-mean-square error (R-RMSE) as

$$\text{R-RMSE} = \frac{\|\mathbf{J}_{\mathrm{NEW}}(\theta) - \mathbf{J}_{\mathrm{MOM}}(\theta)\|_2}{\|\mathbf{J}_{\mathrm{MOM}}(\theta)\|_2} \times 100\% \tag{18}$$

where $\mathbf{J}_{\mathrm{NEW}}(\theta)$ and $\mathbf{J}_{\mathrm{MOM}}(\theta)$ are the current density of local interest region under multi-angle incidence, which can be calculated by the proposed method and MOM, respectively.

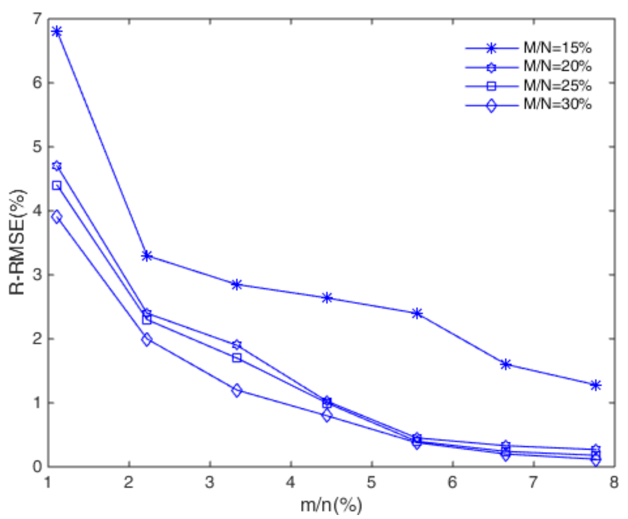
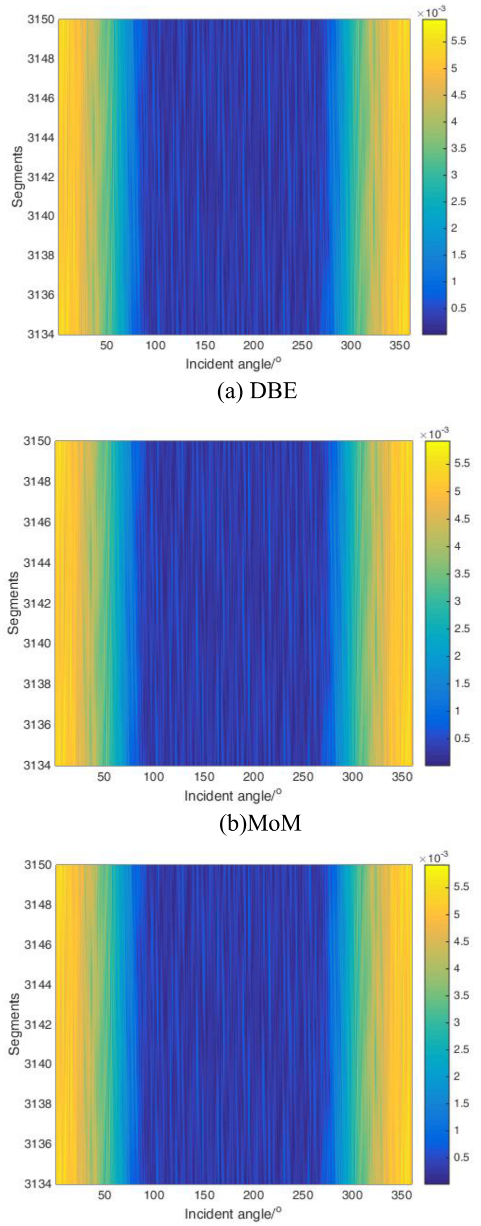


FIGURE 2. The R-RMSE of proposed method in different M/N and m/n for PEC cylinder with a radius of 100λ.

First, considering a PEC cylinder with a radius of 100λ, and the perimeter of cylinder is divided equally into 6284 segments ($N = 6284$) with a step length of 0.1λ.As shown as Fig.2, the computational errors of proposed method are



(a) DBE

(b)MoM

(c)The proposed method

FIGURE 3. The pseudo-color images of current density for a local interest region on PEC cylinder under different incident angles by different methods.

described in different M/N and m/n, in which $M/N = 20\%(M = 1256)$ and $m/n = 5.55\%(m = 20)$ is the optimum factor combination for the computational efficiency. Compared with traditional MOM, M/N means the calculation saving rate of elements filling of impedance matrix Z, and m/n means the saving rate of repeated calculation for 360 incident angles. Although the above test results were obtained by calculating the PEC cylinder under the irradiation of TM plane wave, the results can still be used as reference values for other objects.

By employing AWE,the proposed method accelerate the calculation of the local interest region, and it only consume

TABLE 1. The calculated data for PEC cylinder at different incident angles (1°-360°).

Method	MOM	DBE	The Proposed Method
M/N(%)	100% (M=N=6284)	20% (M=1256,N=6284)	20% (M=1256,N=6284)
m/n (%)	100% (m=n=360)	100% (m=n=360)	5.55% (m=20, n=360)
RRMSE(%)	/	0.27%	0.453%
CPU time(s) of local interest region (AWE)	6889.53	4029.87	358.34s
Memory Usage(MB)	442.94	96.88	27.89

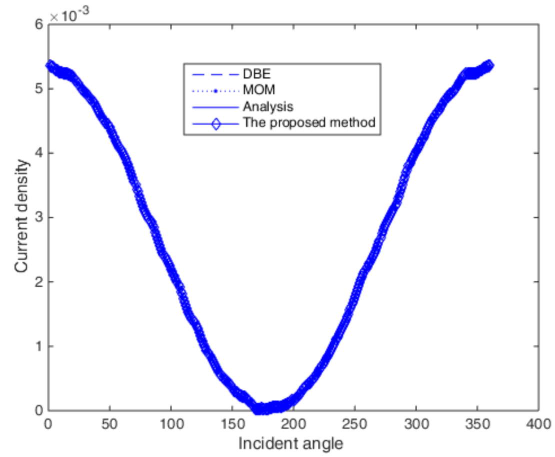


FIGURE 4. The current density of given node on PEC cylinder at different incident angles (1°-360°).

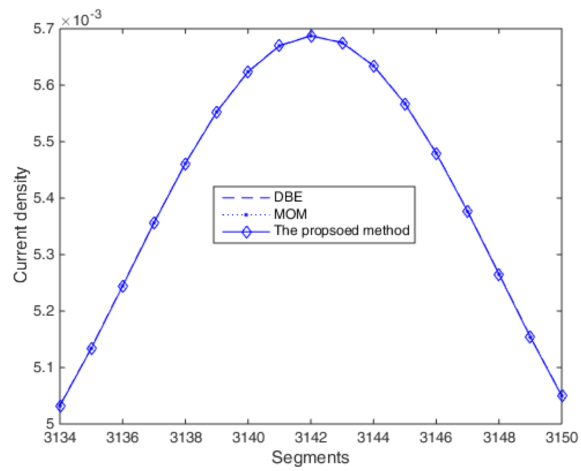
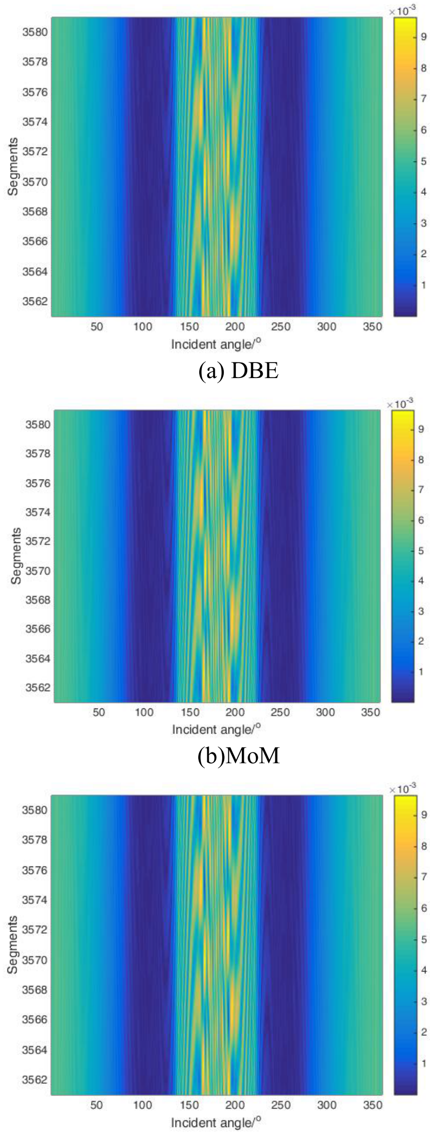


FIGURE 5. The current density of a local interest region on PEC cylinder at 360° incident angle.

358.34s for the local electromagnetic scattering under the excitation of different incident angles (1°-360°), which save the calculation time more than 90% compared with DBE and MOM, respectively. The pseudo-color images are shown in Fig.3, and the relevant calculated data are shown in Table 1.

The current density of given node by TM waves incident from 1° to 360° are described in Fig.4, and the solutions



(a) DBE

(b)MoM

(c)The proposed method

FIGURE 6. The pseudo-color images of current density for a local interest region on PEC warhead model, under different incident angles by different methods.

obtained by the proposed method, DBE method and MOM method are in good agreement with each other. Fig.5 show compared results of current density at different node locations for the PEC cylinder under a fixed incident angle, which are obtained by the proposed method, DBE and MOM, respectively, and they agree well with each other.

As the second example, two dimensional PEC warhead model is considered, whose cross section including a semicircle and a rectangle, and the perimeter of the warhead model is divided equally into 7142 segments ($N = 7142$) with a step length of 0.1λ. As shown in Fig.6, the pseudo-color images calculated by DBE,MOM and the proposed method, respectively, which have a strong consistency. Similarly to the example above, the proposed method also present an accelerated scheme to solve the local electromagnetic scattering at different incident angle (1°-360°) with help of AWE, which consume CPU time is 660.77s, and the computation time is significantly reduced compared to DBE and MOM. The relevant computational information is shown in Table 2.

TABLE 2. The calculated data for PEC warhead model at different incident angles (1°-360°).

METHOD	MOM	DBE	THE PROPOSED METHOD
M/N(%)	100% (M=N=7142)	20% (M=1428,N=7142)	20% (M=1428,N=7142)
m/n (%)	100% (m=n=360)	100% (m=n=360)	5.55% (m=20, n=360)
R-RMSE(%)	/	0.34%	0.56%
CPU TIME(S) OF LOCAL INTEREST REGION (AWE)	11206.04	6405.74	660.77
MEMORY USAGE(MB)	525.68	124.42	36.87

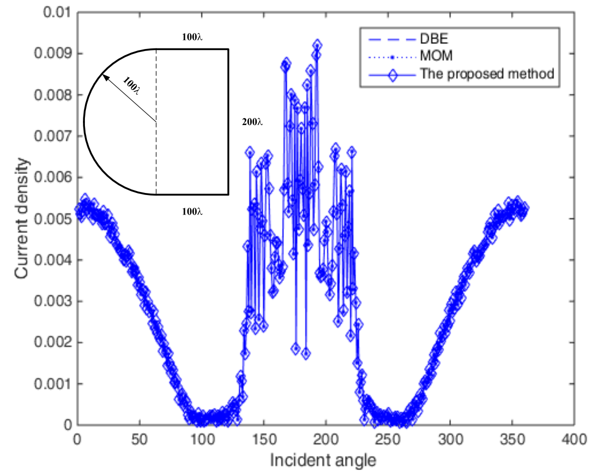


FIGURE 7. The current density of given node on PEC warhead model at different incident angles (1°-360°).

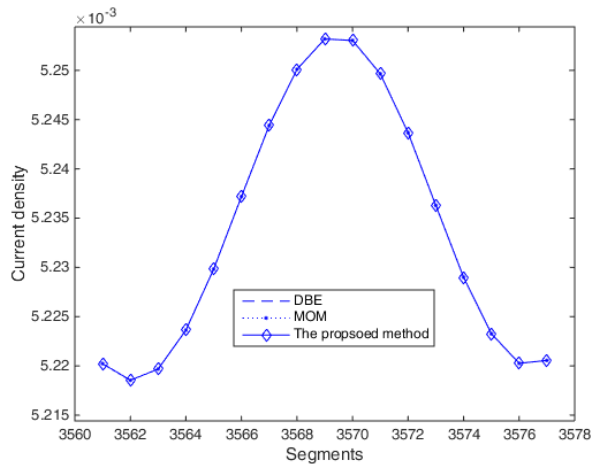


FIGURE 8. The current density of a local interest region on PEC warhead model at 360° incident angle.

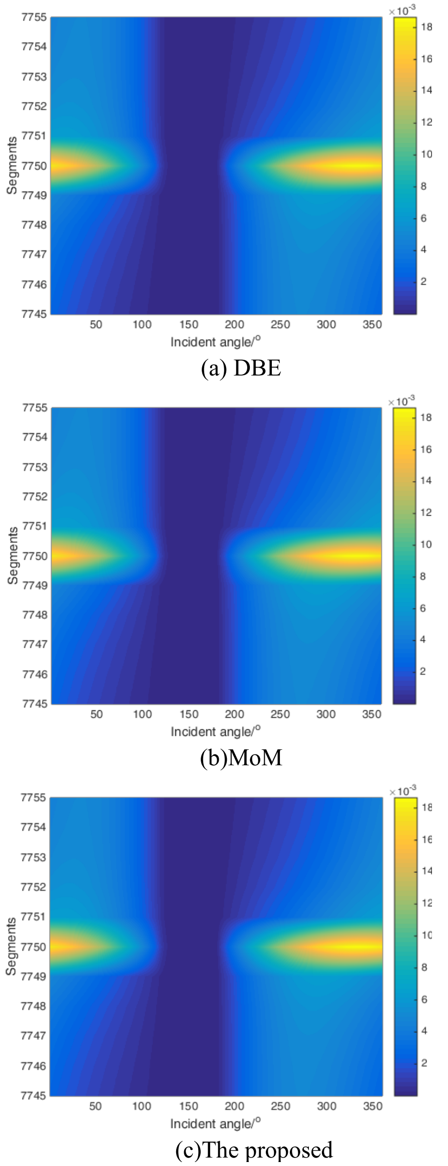


FIGURE 9. The pseudo-color images of current density for local interest region on PEC ship model under different incident angles by different methods.

As shown in Fig.7, under different incident angles, the current density of given node on warhead model are obtained by DBE, MOM, and the proposed method, respectively. Fig.8 show the current densities of a local interest region on PEC warhead model,while the incident angle is 360°.

Finally example, two dimensional PEC ship model is considered, whose perimeter is 280 λ, and it is divided equally into 14000 segments ($N = 14000$) with a step length of 0.02λ. For the local interest region around the vertex of ship model, AWE is ineffective to accelerate node expansion for the proposed method since the abrupt change in the boundary of the model, then we have to calculate repeatedly by changing the position of node. As shown in Fig.9, the pseudo-color images obtained by DBE, MOM and the proposed method

TABLE 3. The calculated data for PEC ship model at different incident angles (1°-360°).

Method	MOM	DBE	The Proposed Method
M/N(%)	100% (M=N=14000)	20% (M=2800, N=14000)	20% (M=2800,N=14000)
m/n (%)	100% (m=n=360)	100% (m=n=360)	5.55% (m=20, n=360)
R-RMSE(%)	/	0.52%	0.83%
CPU time(s) of local interest region (node by node)	21019.74	19405.74	1973.85
Memory Usage(MB)	689.67	157.37	54.45

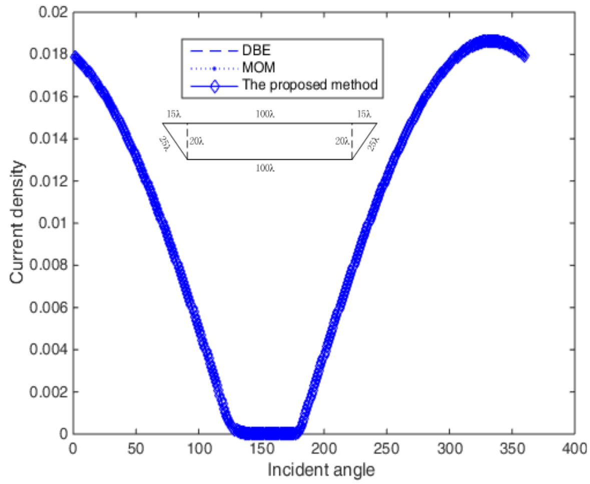


FIGURE 10. The current density of vertex node on PEC ship model at different incident angles (1°-360°).

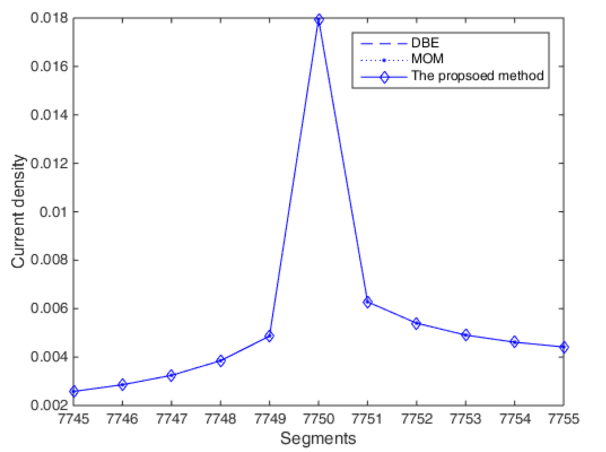


FIGURE 11. The current density of a local interest region including vertex on PEC ship model at 360° incident angle.

agree well, in which the proposed method consume 1973.85s. In this example, although the proposed method uses node by node to repeatedly calculate the solution of local interest region, the CPU time is still significantly less than the traditional algorithm, which benefits from the time advantage of the proposed method in single node calculation, and Table 3 give the relevant computational information data.

Fig.10 show the compared results of wide angle current densities on the vertex node of ship model, which are obtained by the proposed method and traditional methods. At fixed angle of incidence, current densities of local interest region including vertex of the model are given by DBE, MOM and the proposed method, respectively, which is shown in Fig.11.

IV. CONCLUSION

In this paper, a fast and accurate method was proposed to solve local current distribution as electromagnetic scattering of electrically large object over a wide incident angle range was considered. The method can avoid solving all currents on the surface of object, and it have less element filling of impedance matrix and fewer number of repeated calculation for wide angles compared with traditional methods. The simulation results of various objects have validated the high efficiency of the proposed method.

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