Modified Adaptive Cross Approximation Algorithm for Analysis of Electromagnetic Problems

Z. N. Jiang, R. S. Chen, Z. H. Fan, Y. Y. An, M. M. Zhu, and K. W. Leung

Department of Communication Engineering
Nanjing University of Science and Technology, Nanjing, China, 210094
eechenrs@mail.njust.edu.cn

Abstract- In order to efficiently analyze the large dense complex linear system arising from electric field integral equations (EFIE) formulation of electromagnetic scattering problems, the adaptive cross approximation (ACA) is applied to accelerate the matrix-vector multiplication operations. Although the ACA is already efficient compared with the direct method, this paper utilizes a novel technique to further reduce the setup time and storage memory. This method applies the predetermined interaction list supported oct tree (PILOT) to form a new far field interaction list. Using the new far field interaction list, less setup time representation of the far field matrix is obtained. The numerical results of complex objects are used to demonstrate that the memory requirement of the modified ACA is also less than that of the traditional ACA. An efficient preconditioning technique is combined into the inner-outer flexible generalized minimal residual (FGMRES) solver to further speed up the matrix-vector multiplication.

Index Terms- Adaptive cross approximation (ACA), flexible generalized minimal residual (FGMRES), predetermined interaction list supported oct tree (PILOT).

I. INTRODUCTION

Different electromagnetic scattering problems have been studied in recent years. They include, but not limited to, radar cross section (RCS) computations, antenna analysis, remote sensing, biomedicine, electromagnetic interference (EMI), and electromagnetic compatibility (EMC). In this paper, the scattering of the complex objects in free space are analyzed. Simulating these problems is very time demanding, and good numerical methods are required to compute their solutions quickly and efficiently. The method of moments (MoM) [1-6] is one of the most widely used techniques for solving electromagnetic problems. For a large electromagnetic problem, the number of unknowns, N, will be large and it would be difficult to solve the matrix equation. This is because the memory requirement and computational complexity are proportional to $O(N^2)$ and $O(N^3)$, respectively. This difficulty can be circumvented by using the Krylov iterative method, which can reduce the operation count to $O(N^2)$.

To alleviate this problem, many fast solution algorithms have been developed. The most popular fast solution include the multilevel fast multipole algorithm (MLFMA) [7-10], has $O(N\log N)$ complexity for a given accuracy. Though efficient and accurate, this algorithm is highly technical. It utilizes a large number of tools, such as partial wave expansion, exponential expansion, filtering, and interpolation of spherical harmonics. For the MLFMA, however, a *priori* knowledge of the Green's function is needed for the formulation and implementation. As a result, it cannot be easily applied to analyze the layered media problems. ACA is another popular technique used to analyze the scattering/radiation [11], which exploits the well known fact that for well separated sub-scatterers, the corresponding sub-matrices are low rank and can be compressed. In contrast with MLFMA, the ACA is purely algebraic and, therefore, don't depend on the problem Green's function. However, the setup time of the ACA is much more than that of MLFMA. Because of that, the MLFMA reuses multipole and local expansion information across levels, while the ACA does not.

The aim of this paper is to present a modified ACA for solving the electromagnetic problems. It utilizes the predetermined interaction list supported oct tree (PILOT) [12-13] to reduce the setup time and the memory consumption of ACA. An efficient preconditioning technique is combined into the inner-outer flexible generalized minimal residual (FGMRES) solver to speed up the convergence rate of the electric field integral equation (EFIE) [14-17]. Simulation results show that the modified ACA is computationally more efficient than the traditional ACA.

The remainder of this paper is organized as follows. Section II demonstrates the formulation of EFIE. Section III describes the theory and implementation of the modified ACA in more details and gives a brief introduction to the inner-outer flexible generalized minimal residual (FGMRES) method. Numerical experiments are presented to demonstrate the efficiency of this proposed method in Section IV. Conclusions are provided in Section V.

II. Formulation

In this paper, the electric field integral equation (EFIE) is used to analyze electromagnetic scattering problems. The EFIE formulation of electromagnetic wave scattering problems using planar Rao-Wilton-Glisson (RWG) basis functions for surface modeling is presented in [3]. The resulting linear systems from EFIE formulation after Galerkin's testing are briefly outlined as follows

$$\sum_{n=1}^{N} Z_{mn} I_n = V_m, \qquad m = 1, 2, \ldots, N, \tag{1}$$

where

$$Z_{mn} = \frac{jk}{4\pi}\Big(\iint_s \Lambda_m(\mathbf{r})\cdot\iint_s G(\mathbf{r},\mathbf{r}')\Lambda_n(\mathbf{r}')dS'dS - \frac{1}{k^2}\iint_s \nabla\cdot\Lambda_m(\mathbf{r})\cdot\iint_s G(\mathbf{r},\mathbf{r}')\nabla\cdot\Lambda_n(\mathbf{r}')dS'dS\Big), \tag{2}$$

and

$$V_m = \iint_s \Lambda_m(\mathbf{r})\cdot\left(\frac{1}{\eta}\mathbf{E}^i(\mathbf{r})\right)dS, \quad G(\mathbf{r},\mathbf{r}') = \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|}.$$

Here, $G(\mathbf{r},\mathbf{r}')$ refers to the Green's function in free space and $\{I_n\}$ is the column vector containing the unknown coefficients of the surface current expansion with RWG basis functions. Also, as usual, $\mathbf{r}$ and $\mathbf{r}'$ denote the observation and source point locations. $\boldsymbol{E}^i(\mathbf{r})$ is the incident excitation plane wave, and η and k denote the free space impendence and wave number, respectively. N is the number of unknowns used to discretize the object.

Once the matrix equation (1) is solved, the expansion coefficients $\{I_n\}$ can be used to calculate the scattered field and RCS. In the following, we use Z to denote the coefficient matrix in equation (1), $I = \{I_n\}$ and $V = \{V_n\}$ for simplicity. Then, the EFIE matrix equation (1) can be symbolically rewritten as

$$ZI = V. \tag{3}$$

To solve the above matrix equation by an iterative method, the matrix-vector products are needed at each iteration. Traditionally, a matrix-vector production requires the operation cost $O(N^2)$.

III. Modified ACA

A. The oct tree structure

Take three dimensional problems into account; ACA is based on the data structure of the oct tree [8]. In Fig. 1, the box enclosing the object is subdivided into smaller boxes at multiple levels, in the form of an octal tree. The largest boxes not touching each other are at level 2, while the smallest boxes are at level L. The subdivision process runs recursively until the finest level L.

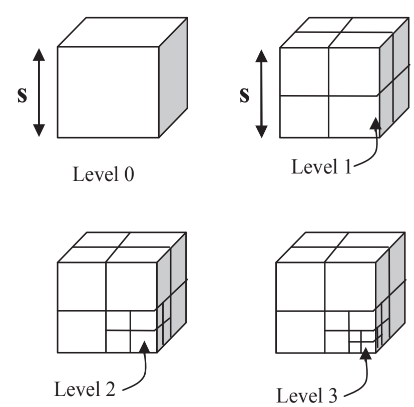


Fig. 1. The sketch of the octree structure.

With reference to Fig. 1, the box has its far interaction box at level 2 or higher. The far interaction boxes can be analyzed using the ACA.

B. Predetermined interaction list supported oct tree (PILOT)

The form of possible far interaction boxes for an observation box in the two dimensional case is shown in the Fig. 2.

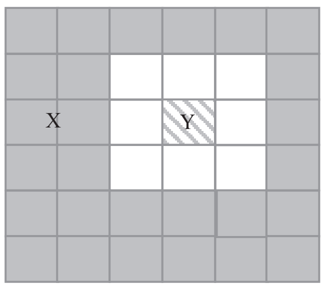
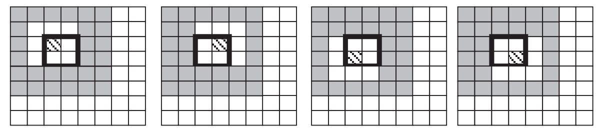


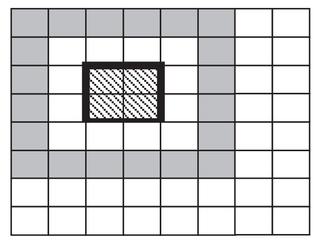
Fig. 2. The form of possible far interaction boxes for an observation box in the two dimensional case.

Where *Y* is the observation box, *X* indicates the far interaction part of *Y*. For each observation box in Fig. 2, there are 27 possible boxes of the far interaction part of the impedance matrix in the two dimensional problems (there are 189 possible boxes in the far interaction part for the three dimensional case). The interaction matrix between the observation box and the box in the far interaction part is filled by ACA [11]. Therefore, the setup time of the traditional ACA is very long. In order to improve the setup time of the traditional ACA, a new far field interaction list called the PILOT algorithm is used in this paper.

According to [13], the PILOT algorithm utilizes the idea that higher compression is achieved when the dimension of the matrix is large. It utilizes that the far field interaction lists of siblings share many common cubes to regroup a new far field interaction list, while further compression is achieved by using the PILOT algorithm. It must be noted that the common interaction list does not directly translate into a merged interaction because the rank of such an interaction submatrix will not in general be low. The common interaction list is decomposed into disjointed parts such that the overall compression is optimized. Each of these disjointed parts is an interaction between grouped source cubes and observer cubes. For simplicity, the two dimensional common interaction list of sibling combination is illustrated in Fig. 3.



(a)



(b)

Fig. 3. (a) Far interaction part of each cube. (b) The common interaction list of sibling combination.

The decomposition of the common interaction list of Fig. 3 (b) into merged interactions is shown in Fig. 4.

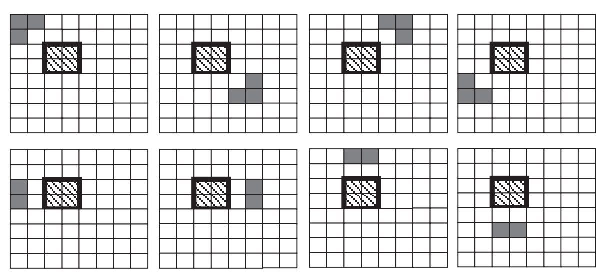


Fig. 4. The decomposition of the common interaction list.

Further compression is possible considering common interaction lists for each pair’s siblings. Thus, the regular interaction list is replaced by the new interaction list. The types of the new interaction for the two dimensional case are shown in Fig. 5.

In [11], there are 108 possible far interaction boxes for each sibling of the traditional ACA in the two dimensional case which is shown in Fig. 3 (a) (there are 1512 possible far interaction boxes for three dimensional case). However, there are only 16 entries with four distinct types (4 entries for the type 1, 4 entries for the type 2, 4 entries for the type 3, and 4 entries for the type 4) of the far interaction for each sibling of the modified ACA which are shown in Fig. 5. The types of the new interaction in the three dimensional case are shown in Fig. 6.

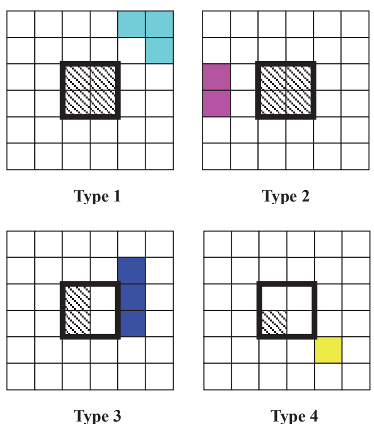


Fig. 5. The types of the interaction in two dimensional case.

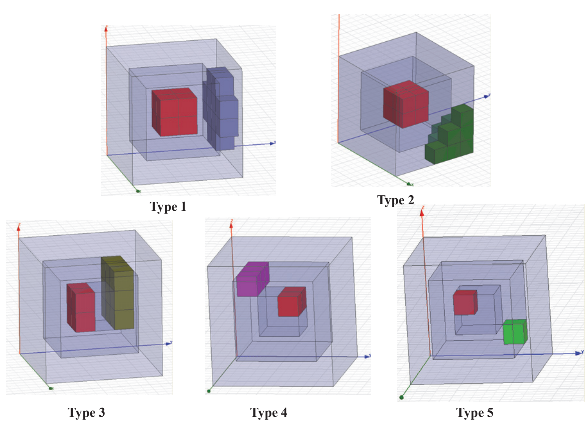


Fig. 6. The types of the interaction in the three dimensional case.

There are 40 entries with five distinct types (6 entries for the type 1 and type 3, 8 entries for the type 2 and type 5, 12 entries for the type 4) of the far interaction for each sibling of the modified ACA. The pattern of the new far field interaction list for a given sibling combination is invariant from that of a different sibling combination at the same level. It is the same for sibling combinations across levels. A higher-level far field interaction list is just a magnified version of that at the lower level.

C. ACA compression of the new interaction list

For the far interaction part of the impedance matrix, its elements are not explicitly computed and stored. Two domains are considered. The first one is an observation domain *i* that contains m_1 basis functions, whereas the second one is a source domain *j* that contains m_2 test functions. When the two domains are sufficiently separated, the impedance matrix associated with them can be expressed using low rank representations [18-20]. This feature is utilized in the ACA. In the ACA implementation, the impedance matrix which is gotten through the EFIE of the two sufficiently separated boxes can be expressed in terms of two small matrices [11]

$$[Z_{ij}]_{m_1 m_2} = [U_{ij}]_{m_1 r}[V_{ij}]_{r m_2}, \tag{4}$$

where $[Z_{ij}]_{m_1 m_2}$ is the interaction matrix between the observation and source domains. The index *r* denotes the rank of the matrix $[Z_{ij}]_{m_1 m_2}$ and is much smaller than m_1 and m_2. Therefore, evaluating the matrix-vector product of the three matrices is much easier than for the direct multiplication.

D. Flexible generalized minimal residual (FGMRES)

In this paper, the FGMRES is used as the iterative solver for the EFIE to further accelerate the convergence [14-17]. Consider the iterative solution of equations of the form *Ax*=*b*. The GMRES algorithm with the right preconditioning solves the modified system $AM^{-1}(Mx)=b$, where the preconditioner *M* is constant. However, in FGMRES, the preconditioner is allowed to vary from one step to another in the outer iteration. We have GMRES for the inner iterations whose preconditioner is chosen as the near interaction of the modified ACA.

IV. NUMERICAL RESULTS

In this section, a number of numerical examples are presented to demonstrate the efficiency of the modified ACA in solving linear systems of electromagnetic scattering problems. The truncating tolerance of the ACA is 10^{-3} (relative to the largest singular value). All numerical experiments were performed in single precision on a Core-2 6300 with 1.86 GHz CPU and 1.96GB RAM. The restart number of the generalized minimal residual (GMRES) is set to be 30 and the stop precision for restarted GMRES is denoted to be 10^{-3}. Both the inner and outer restart numbers of FGMRES are 30. The stop precision for the inner and outer iteration in the FGMRES algorithm is 10^{-2} and 10^{-3}, respectively.

A. Cylinder geometry

First, we consider the scattering of a perfectly electrically conducting (PEC) cylinder at 300 MHz. The height and radius of the cylinder geometry are 1 m and 0.5 m, respectively. The z-axis is used as the rotation axis. It consists of the cylinder geometry with 12990 unknowns. The numerical result of monostatic RCS in theta direction when ϕ is fixed at 0° is depicted in Fig. 7. It can be found that there is an excellent agreement between the result of the modified ACA and that of FEKO. The result validates the accuracy of the modified ACA.

B. The plane-cylinder geometry

The bistatic RCS for the plane-cylinder geometry is shown in Fig. 8. The edge length of the square plane is 4 m, the radius of the small column is 0.1 m, and the height of the small column is 2 m. The rotation axis is the *z*-axis. The frequency is 300 MHz. It can be observed that the result of the proposed method agrees very well with the FEKO. Figures 9 and 10 show the setup time and the memory requirement for the plane-cylinder geometry as a function of the number of unknowns. With reference to Fig. 9, the setup time of the modified ACA is much less than that of the traditional ACA. With reference to Fig. 10, the memory requirement of the modified ACA is also much less than that of the traditional ACA.

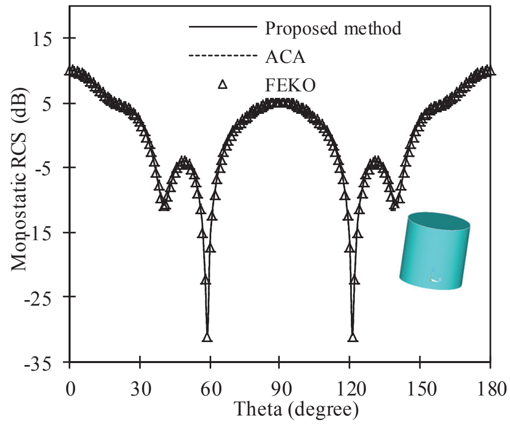


Fig. 7. The monostatic RCS for the cylinder geometry.

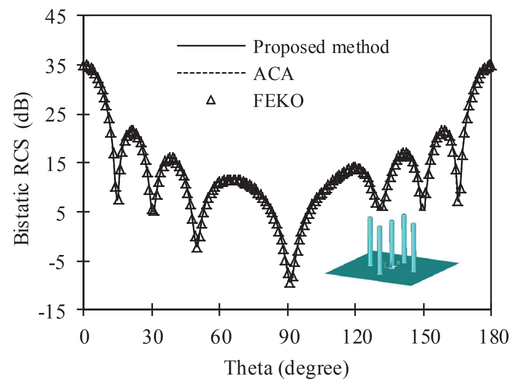


Fig. 8. The bistatic RCS for the plane-cylinder geometry.

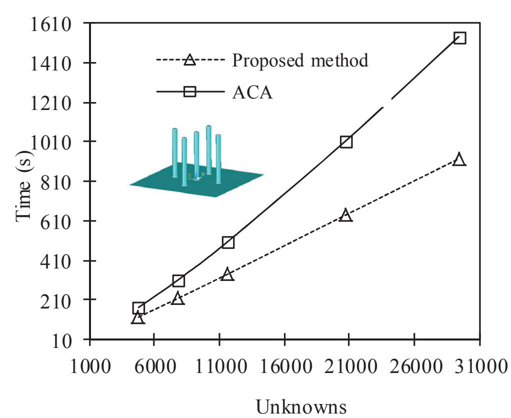


Fig. 9. The setup time for the plane-cylinder geometry.

Figure 11 gives the convergence history curves of the modified ACA solved with GMRES and FGMRES. The geometry is discretized with 29411 unknowns at 300 MHz. In this numerical experiment, GMRES requires 4884 s with 5182 iterative steps, while FGMRES requires only 567 s with 320 outer iterative steps. The solving time of GMRES is 8 times longer than that of FGMRES in this example.

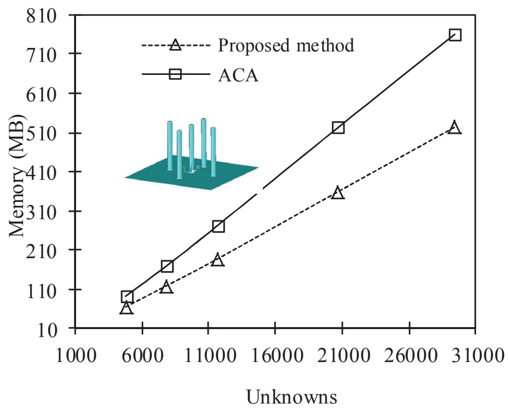


Fig. 10. The memory requirement for the plane-cylinder geometry.

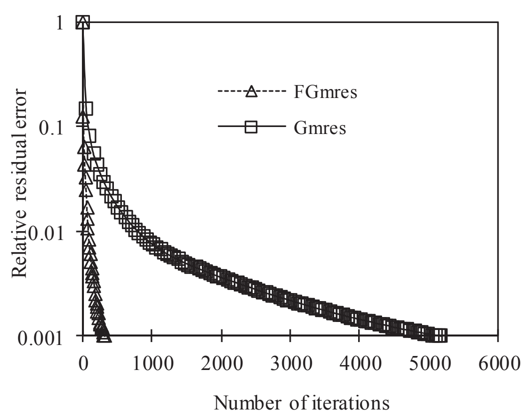


Fig. 11. Convergence histories of the proposed method for the plane-cylinder geometry solved with GMRES and FGMRES.

C. The VIAS geometry

The third example is the VIAS geometry [21]. The geometry fits within a cuboid with an aspect ratio $6:5:0.5$, and the maximum dimension is 4λ at 200 MHz. Figure 12 shows that the result of the proposed method agrees very well with the FEKO. The setup time and the memory requirement for the VIAS geometry as a function of the number of unknowns are shown in Figs. 13 and 14, respectively. With reference to Fig. 13, the setup time of the modified ACA is much less than that of the traditional ACA. It can be observed that the memory requirement of the modified ACA is also much less than that of the traditional ACA according to Fig. 14.

In order to compare the efficiency of the FGMRES with that of GMRES, the plots for the convergence steps and the solve times of the proposed method are provided in Fig. 15 and Fig. 16. It can be found that the solving time of GMRES is 6 times longer than that of FGMRES in this example.

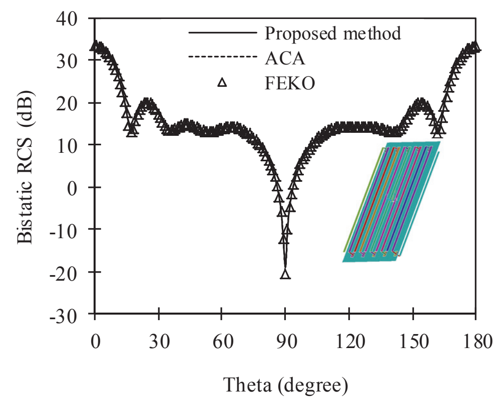


Fig. 12. The bistatic RCS for the VIAS geometry.

V. CONCLUSIONS

In this paper, a modified ACA is proposed for the electromagnetic problems. The proposed method utilizes the PILOT algorithm to reduce the setup time of the ACA, while it does not increase the memory consumption of the ACA. The numerical results demonstrate that setup time of the modified ACA is much less than that of the traditional ACA, while the memory consumption of the modified ACA is also less than that of the

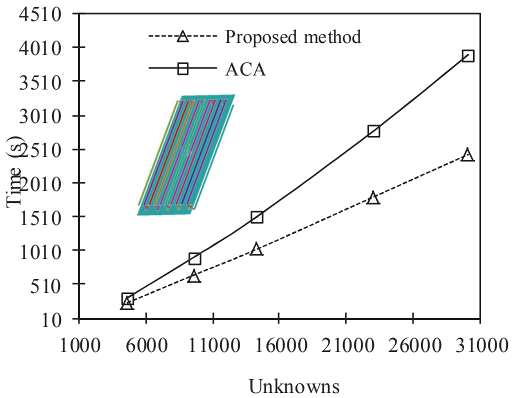


Fig. 13. The setup time for the VIAS geometry.

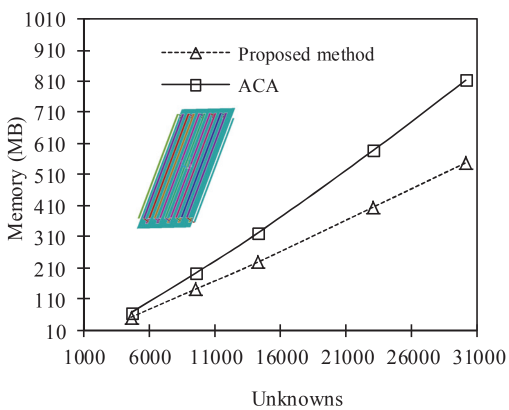


Fig. 14. The memory requirement for the VIAS geometry.

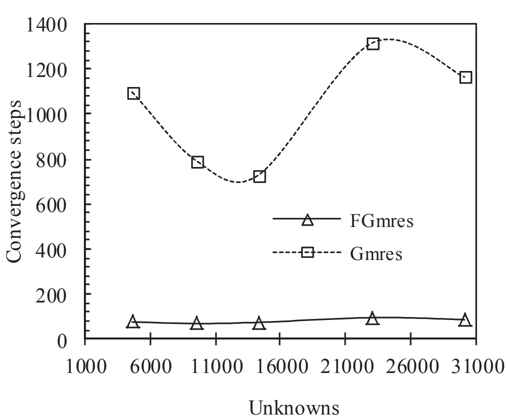


Fig. 15. The convergence steps for the VIAS geometry.

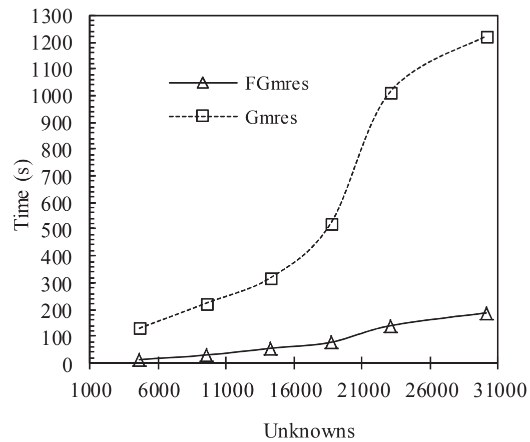


Fig. 16. The solving times for the VIAS geometry.

traditional ACA. With the application of the new far field interaction lists, an efficient version of ACA is obtained in this paper, while the accuracy of the modified ACA is controllable. It is observed that the convergence rate of GMRES is remarkably accelerated by the application of FGMRES algorithm. The proposed method is very efficient for analyzing the electromagnetic scattering problems.

ACKNOWLEDGMENT

We would like to thank the support of Major State Basic Research Development Program of China (973 Program: 2009CB320201); Natural Science Foundation of 60871013, 60701004, 60928002; Jiangsu Natural Science Foundation of BK2008048.

REFERENCES

[1] K. A. Michalski and D. L. Zheng, “Electromagnetic Scattering and Radiation by Surfaces of Arbitrary Shape in Layered Media, Part I: Theory,” *IEEE Trans. Antennas Propag,* vol. 38, no. 3, pp. 335-344, 1990.

[2] K. A. Michalski and D. L. Zheng, “Electromagnetic Scattering and Radiation by Surfaces of Arbitrary Shape in Layered Media, Part II: Implementation and Results for Contiguous Half-Spaces,” *IEEE Trans. Antennas Propag,* vol. 38, no. 3, pp. 345-352, 1990.

[3] S. M. Rao, D. R. Wilton, and A. W. Glisson, ‘‘Electromagnetic Scattering by Surfaces of Arbitrary Shape,’’ *IEEE Trans. Antennas Propagat.*, vol. 30, no. 3, pp. 409-418, May 1982.

[4] E. H. Newman and D. Forrai, ‘‘Scattering from a Microstrip Patch,’’ *IEEE Trans. Antennas Propagat.*, vol. AP-35, pp. 245-251, Mar. 1987.

[5] W. Zhuang, R. S. Chen, D. Z. Ding, and D. X. Wang, “An Efficient Analysis of Frequency Selective Surface in Spectral Domain with RWG Basis Functions,” *Microw Opt. Technol. Lett*, vol. 51, no. 11, pp. 2567-2570, Nov. 2009.

[6] K. A. Michalski and C. G. Hsu, ‘‘RCS Computation of Coax-Loaded Microstrip Patch Antennas of Arbitrary Shape,’’ *Electromagn*., vol. 14, pp. 33-62, Jan.-Mar. 1994.

[7] R. Coifman, V. Rokhlin, and S. Wandzura, “The Fast Multipole Method for the Wave Equation: A Pedestrian Prescription,” *IEEE Antennas Propag. Mag.*, vol. 35, no. 6, pp. 7-12, Jun. 1993.

[8] W. C. Chew, J. M. Jin, E. Michielssen, and J. Song, *Fast Efficient Algorithms in Computational Electromagnetics*, Boston, MA: Artech House, 2001.

[9] H. Zhao, J. Hu, and Z. Nie, "Parallelization of MLFMA with Composite Load Partition Criteria and Asynchronous Communication," *Applied Computational Electromagnetic Society (ACES) Journal*, vol. 25, no. 2, pp. 167-173, 2010.

[10] H. Fangjing, N. Zaiping, and H. Jun, "An Efficient Parallel Multilevel Fast Multipole Algorithm for Large-scale Scattering Problems," *Applied Computational Electromagnetic Society (ACES) Journal*, vol. 25, no. 4, pp. 381-387, 2010.

[11] K. Zhao, M. N. Vouvakis, and J. F. Lee, “The Adaptive Cross Approximation Algorithm for Accelerated Method of Moments Computations of EMC Problems,” *Trans. on Elec. Comp*., vol. 47, no. 4, pp. 763-773, Nov. 2005.

[12] D. Gope and V. Jandhyala, “Oct-Tree-Based Multilevel Low-Rank Decomposition Algorithm for Rapid 3-D Parasitic Extraction,” *IEEE Trans. Computer-Aided Design*, vol. 23, no. 4, pp. 1575-1580, Nov. 2004.

[13] D. Gope, and V. Jandhyala, “Efficient Solution of EFIE via Low-Rank Compression of Multilevel Predetermined Interactions,” *IEEE Trans. Antennas Propagat.*, vol. 53, no. 10, pp. 3324-3333, Oct. 2005.

[14] Y. Saad and M. H. Schultz, “GMRES: A Generalized Minimal Residual Algorithm for Solving Nonsymmetric Linear Systems,” *SIAM J. Sci. Statist. Comput*, vol. 7, pp. 856-869, Jul. 1986.

[15] Y. Saad, “A Flexible Inner-Outer Preconditioned GMRES Algorithm,” *SIAM J. Sci. Statist. Comput*., vol. 14, pp. 461-469, 1993.

[16] R. S. Chen, D. Z. Ding, Z. H. Fan, E. K. N. Yung, and C. H. Chan, “Flexible GMRES-FFT Method for Fast Matrix Solution: Application to 3D Dielectric Bodies Electromagnetic Scattering,” *Int. J. Numer. Model: Electronic. Networks, Devices and Fields*, vol. 17, pp. 523-537, 2004.

[17] R. S. Chen, Y. Q. Hu, Z. H. Fan, D. Z. Ding, D. X. Wang, and E. K. N. Yung, “An Efficient Surface Integral Equation Solution to EM Scattering by Chiral Objects above a Lossy Half Space,” *IEEE Trans. Antennas Propag*, vol. 57, no. 11, pp. 3586-3593, Nov. 2009.

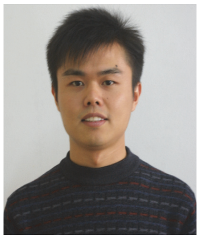
[18] E. Michielssen and A. Boag, “A Multilevel Matrix Decomposition Algorithm for Analyzing Scattering from Large Structures,” *IEEE Trans. Antennas Propag*, vol. 44, no. 8, pp. 1086-1093, Aug. 1996.

[19] A. Heldring, J. M. Tamayo, J. M. Rius, and J. Parron, “Multilevel MDA-CBI for Fast Direct Solution of Large Scattering and Radiation Problems,” *IEEE AP-S International Symposium 2007*, Honolulu, Hawaii, USA, 10-15 June 2007.

[20] J. M. Rius, J. Parron, E. Ubeda, and J. Mosig, “Multilevel Matrix Decomposition Algorithm for Analysis of Electrically Large Electromagnetic Problems in 3-D,” *Microw Opt. Technol. Lett*, vol. 22, no. 3, pp. 177-182, Aug. 1999.

[21] J. Cheng, S. A. Maloney, R. J. Adams, and F.

X. Canning, “Efficient Fill of a Nested Representation of the EFIE at Low Frequencies,” *IEEE Antennas and Propagation Society Int. Symp.*, pp. 1-4, 2008.



Zhaoneng Jiang was born in Jiangsu Province, the People’s Republic of China. He received the B.S. degree in Physics from Huaiyin Normal College in 2007, and is currently working toward the Ph.D. degree at Nanjing University of Science and Technology (NJUST), Nanjing, China. His current research interests include computational electromagnetics, antennas and electromagnetic scattering and propagation, and electromagnetic modeling of microwave integrated circuits.

Ru-Shan Chen (M’01) was born in Jiangsu, P. R. China. He received his B.Sc. and M.Sc. degrees from the Dept. of Radio Engineering, Southeast University, in 1987 and in 1990, respectively, and his Ph.D. from the Dept. of Electronic Engineering, City University of Hong Kong in 2001. He joined the Dept. of Electrical Engineering, Nanjing University of Science & Technology (NJUST), where he became a Teaching Assistant in 1990 and a Lecturer in 1992. Since September 1996, he has been a Visiting Scholar with the Department of Electronic Engineering, City University of Hong Kong, first as Research Associate, then as a Senior Research Associate in July 1997, a Research Fellow in April 1998, and a Senior Research Fellow in 1999. From June to September 1999, he was also a Visiting Scholar at Montreal University, Canada. In September 1999, he was promoted to Full Professor and Associate Director of the Microwave & Communication Research Center in NJUST and in 2007, he was appointed Head of the Dept of Communication Engineering, Nanjing University of Science & Technology. His research interests mainly include microwave/millimeter-wave systems, measurements, antenna, RF-integrated circuits, and computational electromagnetics. He is a Senior Member of the Chinese Institute of Electronics (CIE). He received the 1992 third-class science and technology advance prize given by the National Military Industry Department of China, the 1993 third class science and technology advance prize given by the National Education Committee of China, the 1996 second-class science and technology advance prize given by the National Education Committee of China, and the 1999 first-class science and technology advance prize given by JiangSu Province as well as the 2001 second-class science and technology advance prize. At NUST, he was awarded the Excellent Honor Prize for academic achievement in 1994, 1996, 1997, 1999, 2000, 2001, 2002, and 2003. He has authored or co-authored more than 200 papers, including over 140 papers in international journals. He is the recipient of the Foundation for China Distinguished Young Investigators presented by the National Science Foundation (NSF) of China in 2003. In 2008, he became a Chang-Jiang Professor under the Cheung Kong Scholar Program awarded by the Ministry of Education, China.

Zhen-Hong Fan was born in Jiangsu, the People’s Republic of China in 1978. He received the M.Sc. and Ph.D. degrees in Electromagnetic Field and Microwave Technique from Nanjing University of Science and Technology (NJUST), Nanjing, China, in 2003 and 2007, respectively. During 2006, he was with the Center of Wireless Communication in the City University of Hong Kong, Kowloon, as a Research Assistant. He is currently an associated Professor with the Electronic Engineering of NJUST. He is the author or coauthor of over 20 technical papers. His current research interests include computational electromagnetics, electromagnetic scattering, and radiation.

Yuyuan An was born in Sichuan Province, the People’s Republic of China. He received the B.S. degree in Physics from Nanjing University of Science and Technology (NJUST) in 2009, and is currently working toward the Ph.D. degree at

Nanjing University of Science and Technology (NJUST), Nanjing, China. His current research interests include computational electromagnetics, antennas and electromagnetic scattering and propagation, and electromagnetic modeling of microwave integrated circuits.

Maomao Zhu was born in Anhui Province, the People's Republic of China. She received the B.S. degree in Physics from Anhui University in 2009, and is currently working toward the M.S. degree at Nanjing University of Science and Technology (NJUST), Nanjing, China. Her current research interests include computational electromagnetics, antennas and electromagnetic scattering and propagation, and electromagnetic modeling of microwave integrated circuits.

Kwok Wa Leung was born in Hong Kong SAR. He received his B.S. (Electronics) and Ph.D. (Electronic Engineering) from the Chinese University of Hong Kong in 1990 and 1993, respectively. From June 1988 to August 1989, he spent 15 months as a student trainee in the RF division of Motorola (HK) Limited. In 1994, he joined the City University of Hong Kong (CityU) as an Assistant Professor and is currently a Professor. From Jan.-June 2006, he was a Visiting Professor in the Department of Electrical Engineering, The Pennsylvania State University, USA. He was the Leader of the Departmental Graduate Research Programmes and of the B.Eng. (Honors) Programme in Electronic and Communication Engineering at City University. Professor Leung was the Chairman of the IEEE AP/MTT Hong Kong Joint Chapter for the years of 2006 and 2007. He was the Co-Chair of the Technical Program Committee, IEEE TENCON, Hong Kong, Nov. 2006, and was the Finance Chair of PIERS 1997, Hong Kong. He is currently the Chairman of the Technical Program Committee, 2008 Asia-Pacific Microwave Conference. His research interests include RFID tag antennas, dielectric resonator antennas, microstrip antennas, wire antennas, guided wave theory, numerical methods in electromagnetics, and mobile communications. He serves as an Editor for HKIE Transactions. He also serves as an Associate Editor for IEEE Transactions on Antennas and Propagation and for IEEE Antennas and Wireless Propagation Letters. Professor Leung received the International Union of Radio Science (USRI) Young Scientists Awards in 1993 and 1995, awarded in Kyoto, Japan and St. Petersburg, Russia, respectively. He is a Fellow of HKIE and a Senior Member of IEEE.