A General MoM-PO Hybrid Framework for Modelling Complex Antenna Arrays Mounted on Extremely Large Platform (Invited Paper)

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Abstract- **A general method of moments (MoM) - physical optics (PO) hybrid framework is proposed to fast and efficiently analyze complex antenna arrays installed on extremely large-scale platforms. In this general MoM-PO hybrid framework, MoM is applied to simulate the antenna array and the integral equations can be flexibly set up either on the antenna array or on a Huygens surface enclosing the antenna array. PO is employed to efficiently describe the contribution of the electrically large platform and an iterative process is implemented to take the interaction between the antenna array and the platform into account. To further reduce the peak memory usage and CPU time, the adaptive integral method (AIM) is adopted to speed up the solving of MoM equations. Numerical results show that the proposed general MoM-PO hybrid technique can greatly reduce the CPU time and peak memory usage compared with the conventional MoM-PO method.**

I. INTRODUCTION

Onboard antenna placement is an important problem in EMC study and antenna design, especially for complex antenna arrays on large-scale platforms. An efficient iterative method of moments (MoM) – physical optics (PO) technique has been proposed [1], where the antenna array is modeled by MoM, and the electrically large platform is simulated by PO. Then MoM and PO is hybridized through an iterative process to take the interaction between antenna array and platform into account. The efficient iterative MoM-PO (EI-MoM-PO) can greatly reduce the number of unknowns and CPU time in the analysis of onboard antenna arrays with large-scale platforms, and the ground effects can also be coupled into the iterative framework to solve half-space problems [2]. However, the capability and accuracy of EI-MoM-PO depends on whether the antenna array can be accurately calculated with MoM.

On the other hand, a lot of commercial software and testing facilities can well simulate or measure the performance of complex antenna arrays. Therefore, to enhance the capability of the EI-MoM-PO technique, a general MoM-PO hybrid framework is proposed where the Huygens principle is combined with EI-MoM-PO. In this general MoM-PO framework, a Huygens surface, which encloses the complex antenna array, is introduced to replace the antenna array. On the Huygens surface, the equivalent electric and magnetic currents are defined and MoM equations are established. The initial MoM currents depend on the electromagnetic fields radiated from the antenna array on the Huygens surface, which can be given by measurement or simulating with commercial software. Then the iterative process is implemented between MoM and PO to consider the interaction of the antenna array and the platform.

For large and complex antenna array, the MoM part still consumes a large amount of memory and CPU time. To further improve the efficiency of the proposed general MoM-PO technique, the adaptive integral method (AIM) [3] is adopted to reduce the peak memory usage and speed up the solving of MoM equations. Numerical results show very good capability and accuracy of the general MoM-PO hybrid framework.

II. FORMULATION

A. Efficient Iterative MoM-PO Method

Consider an electromagnetic system consisting of antennas and the PEC platform where the integral equations can be established as

$$\vec{E}^s = L^E \vec{J} - C\vec{K}\,, \tag{1}$$

$$\vec{H}^s = C\vec{J} + L^H \vec{K}\,, \tag{2}$$

where the operators $L^E \vec{X}$, $L^H \vec{X}$ and $C\vec{X}$ are given by

$$L^E \vec{X} = -j\omega\mu\int_{S'} \vec{X} G(\vec{r},\vec{r}')dS' + \frac{1}{j\omega\varepsilon}\nabla\int_{S'} \nabla'\cdot\vec{X} G(\vec{r},\vec{r}')dS'\,, \tag{3}$$

$$L^H \vec{X} = -j\omega\varepsilon\int_{S'} \vec{X} G(\vec{r},\vec{r}')dS' + \frac{1}{j\omega\mu}\nabla\int_{S'} \nabla'\cdot\vec{X} G(\vec{r},\vec{r}')dS'\,, \tag{4}$$

$$C\vec{X} = \nabla\times\int_{S'} \vec{X} G(\vec{r},\vec{r}')dS'\,. \tag{5}$$

$G(\vec{r},\vec{r}')$ is the free space Green's function. $\vec{J}$ and $\vec{K}$ are the induced electric and magnetic currents due to feed of antenna.

Then MoM is applied to the analysis of the antenna array and PO is used to approximate contribution of the electrically large platform. By employing proper boundary conditions, one can set up the MoM matrix equation only for MoM-region

$$\begin{bmatrix} Z_{km}^{EE} & Z_{km}^{EH} \\ Z_{km}^{HE} & Z_{km}^{HH} \end{bmatrix} \begin{bmatrix} I_m^{0,MoM} \\ K_m^{0,MoM} \end{bmatrix} = \begin{bmatrix} V_k^E \\ V_k^H \end{bmatrix}. \tag{6}$$

Solving equation (6) yields the electric and magnetic currents in MoM-region, and these currents are regarded as the sources for PO-region (PEC platform) to calculate the induced PO current

$$\bar{J}^{1,PO} = \sum_{m=1}^{M}[2\delta\hat{n}\times(I_m^{0,MoM}C\bar{f}_m + K_m^{0,MoM}\bar{L}^H\bar{f}_m)], \quad (7)$$

where $\hat{n}$ is the outer unit normal of PO-region. δ is the shadowing effect coefficient, and $\bar{f}_m$ is the MoM basis function.

To consider the effects of the platform on the antenna array, additional exciting voltages due to $\bar{J}^{1,PO}$ are added to the right side of the MoM matrix equation (6), which are expressed as

$$\Delta V_k^{E,1} = -<\bar{f}_k, \bar{L}^E\bar{J}_S^{1,PO}>, \quad (8)$$

$$\Delta V_k^{H,1} = -<\bar{f}_k, C\bar{J}_S^{1,PO}>. \quad (9)$$

Substituting the modified sources $V_k^E + \Delta V_k^{E,1}$ and $V_k^H + \Delta V_k^{H,1}$ into (6) obtains the new MoM currents in the presence of the platform. An iterative process will be implemented from equation (6) to (9) by replacing the superscript "*1*" with the number of iteration "*i*", until the errors of MoM currents $\|[I_m^{i,MoM}]-[I_m^{i-1,MoM}]\|/\|[I_m^{i-1,MoM}]\|$ and $\|[K_m^{i,MoM}]-[K_m^{i-1,MoM}]\|/\|[K_m^{i-1,MoM}]\|$ are not more than the prescribed threshold.

B. General Hybrid MoM-PO Framework

In practice, some types of widely used antenna arrays can not be well simulated with MoM, such as Vivaldi arrays. To enhance the capability of EI-MoM-PO technique, the Huygens principle is introduced into this hybrid framework, and the MoM equations in (6) can just be established on a Huygens surface, which covers the antenna array, instead of on the antenna array. The iterative process form (6) to (9) should also be implemented to consider the interaction between the antenna array and the platform. A difference between this general MoM-PO hybrid framework and the EI-MoM-PO is that the initial MoM currents $I_m^{0,MoM}$ and $K_m^{0,MoM}$ are determined by electric and magnetic fields on the Huygens surface radiated from the antenna array. These fields can be obtained from measurement or simulated results with commercial software. Therefore, most types of antenna arrays can be handled with this proposed general MoM-PO hybrid technique.

C. Acceleration with Adaptive Integral Method

It's very time-consuming to analyze large and complex antenna array with MoM, and a great number of unknowns are required. To overcome this difficulty, AIM can be applied to the MoM part of the proposed general MoM-PO hybrid framework to reduce the memory requirement and speed up the matrix-vector multiplication process $[Z][I]$ when we try to solve (6) with iterative method, such as BiCGStab or GMRES. The matrix vector multiplication $[Z][I]$ can be accelerated as follows:

(i). spliting the matrix-vector multiplication $[Z][I]$ into near interaction term $[Z]^{near}[I]$ and far interaction term $[Z]^{far}[I]$;

(ii). directly computing the near interaction $[Z]^{near}$;

(iii). projecting the MoM basis function to the grid points;

(iv). calculating near interaction term $[Z]^{near}[I]$ directly and the far interaction term $[Z]^{far}[I]$ using FFT;

It should be mentioned that procedures (i) - (iii) just need to be executed once when AIM is implemented for the first time. Within each iterative process between MoM and PO, one just needs to run the iterative solver to get the MoM currents. So the efficiency of the general MoM-PO technique can be greatly improved.

III. NUMERICAL RESULTS

A 24×6 longitude waveguide slot array mounted on an aircraft is simulated with the proposed hybrid technique, as shown in Figure 1. The working frequency of the slot array is 10 GHz and the corresponding wavelength is 0.03 m. The length of the aircraft is 47 m and wingspan is 38.05 m, which are more than 1500λ and 1200λ, respectively. The BJ-100 waveguide is used in the design of the slot array and the details of the array are depicted in Figure 2. Taylor distributions are adopted along the two directions of the slot array aperture. The aperture distributions and the array factor patterns are illustrated in Figure 3 to Figure 6.

This model is simulated serially on a Linux server equipped with an Intel Xeon CPU at 3.1 GHz and 128 GB of RAM. The gain patterns in three cut-planes obtained from the proposed general MoM-PO and the conventional MoM-PO of FEKO are plotted in Figure 7 to Figure 9, and show good agreement. The general MoM-PO only takes 172.5 hours to get the results, while the conventional MoM-PO of FEKO needs 1492.3 hours. The peak memory usage of proposed general MoM-PO and the conventional MoM-PO of FEKO is 1.5 GB and 79.7 GB, respectively. We also try MLFMA of FEKO to handle this model. However, it is too large for MLFMA of which the peak memory usage is 278 GB. So we just show MLFMA results of the waveguide slot array for comparison. From Figure 7 to Figure 9, it can be obviously seen that the gain pattern of the slot array is disturbed by the aircraft. Figure 10 displays the 3D gain pattern of the slot array and Figure 11 depicts the 3D gain pattern of the array installed on the aircraft and the PO current on the platform. By comparing the two 3D gain patterns, the effect from the platform can be more clearly observed.

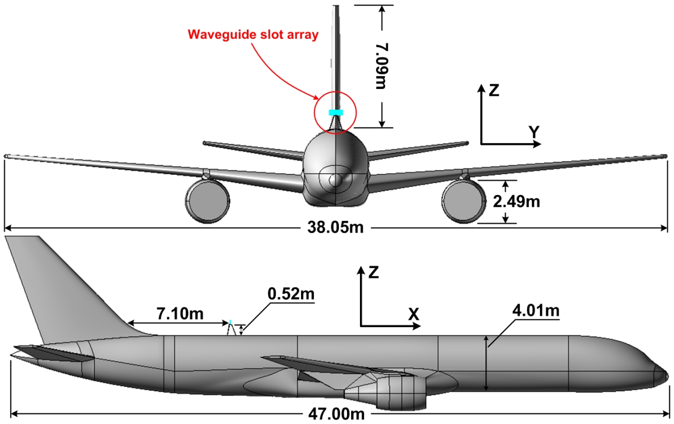

Figure 1. A 24×6 waveguide slot array mounted on an aircraft.

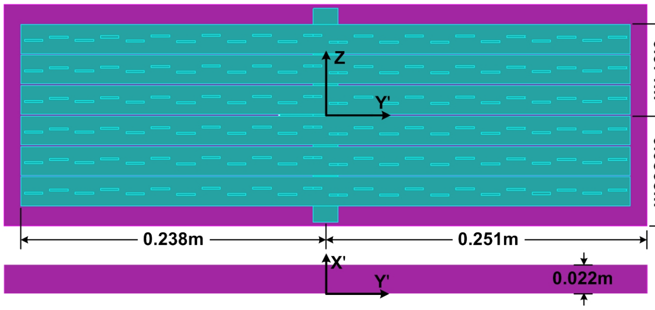

Figure 2. Gain pattern in XOY plane.

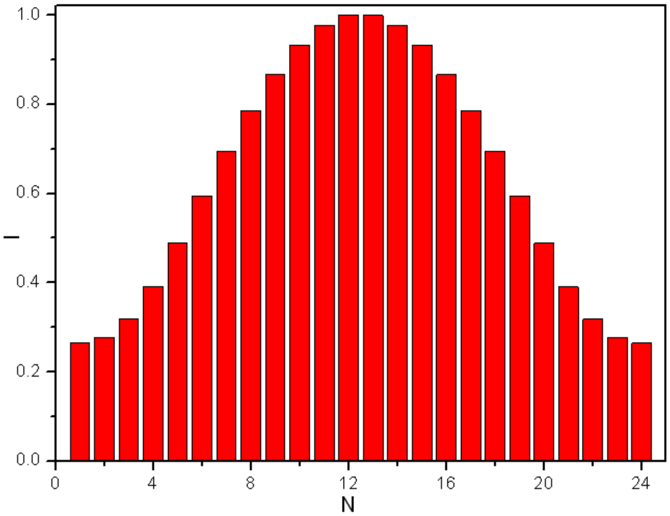

Figure 3. The aperture distribution of a 24-element linear Taylor array.

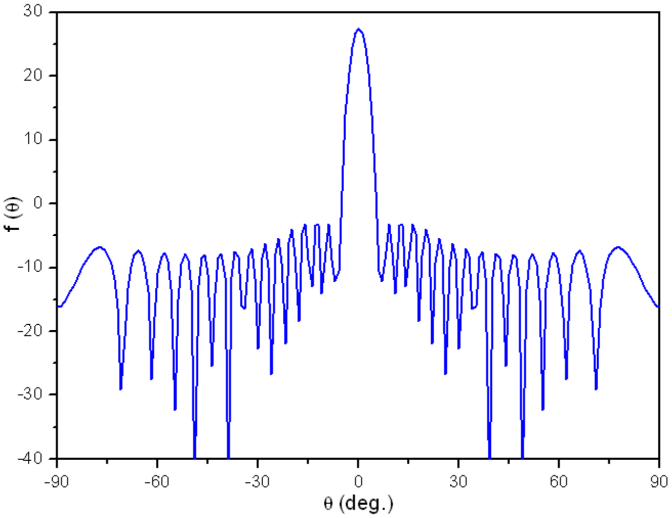

Figure 4. Array factor pattern of a 24-element linear Taylor array.

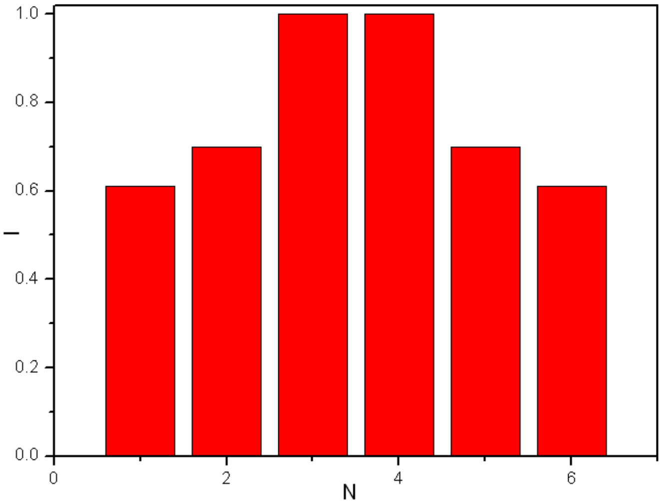

Figure 5. The aperture distribution of a 6-element linear Taylor array.

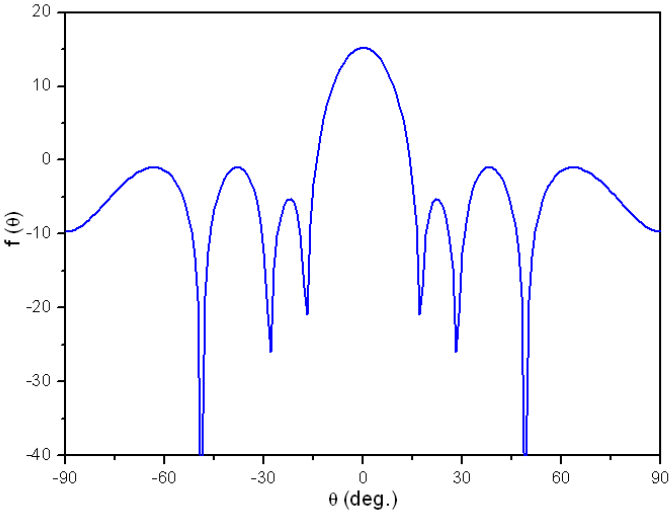

Figure 6. Array factor pattern of a 6-element linear Taylor array.

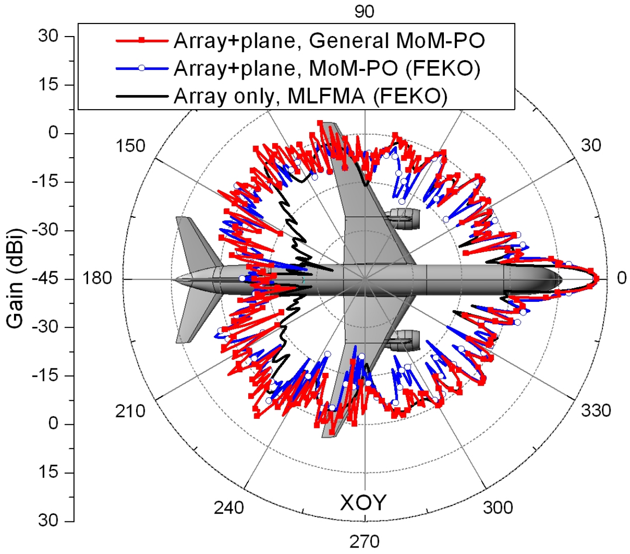

Figure 7. Gain pattern in XOY plane.

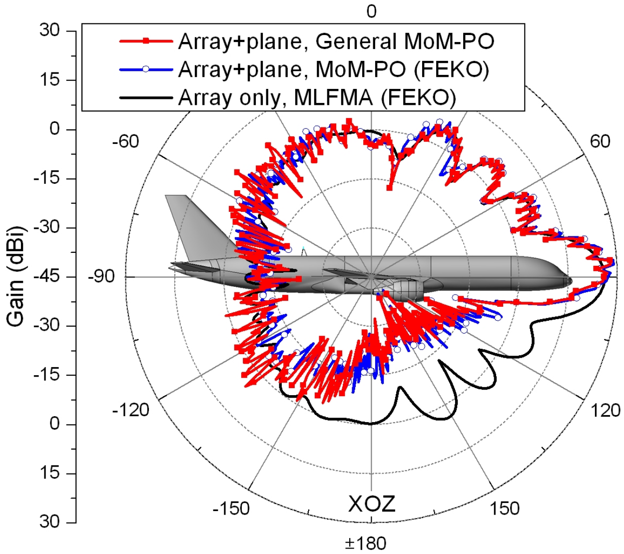

Figure 8. Gain pattern in XOZ plane.

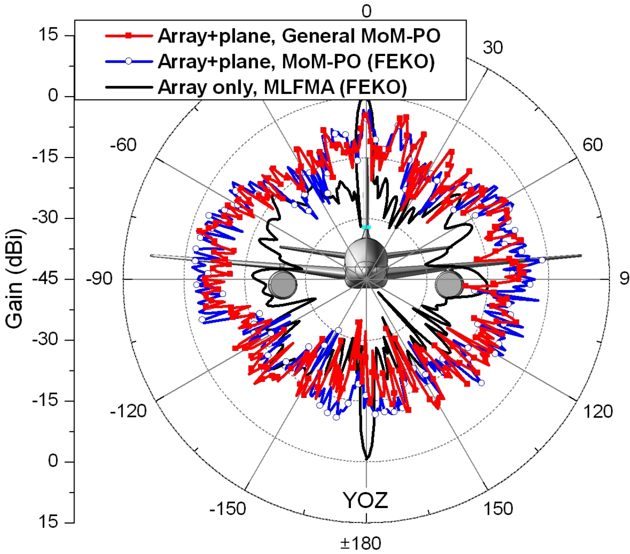

Figure 9. Gain pattern in YOZ plane.

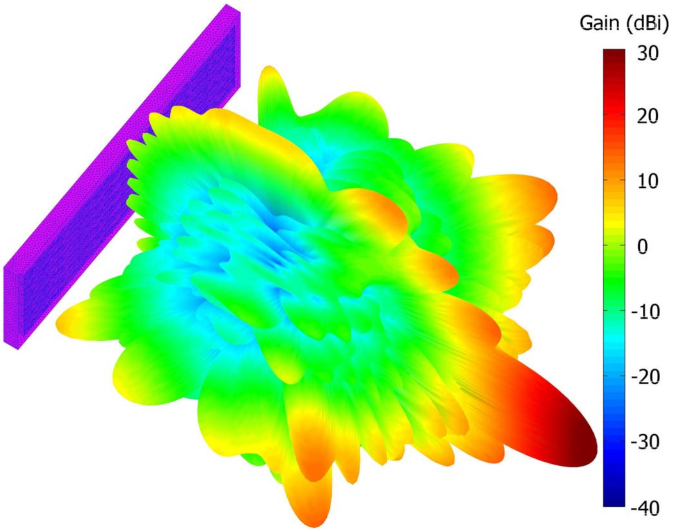

Figure 10. 3D gain pattern of the waveguide slot array

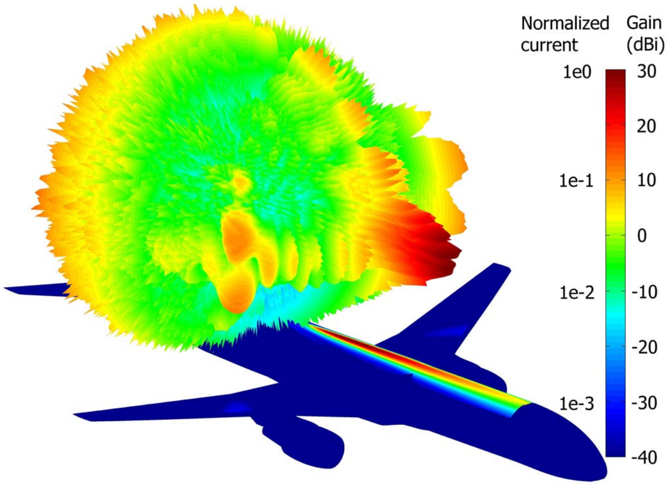

Figure 11. PO current and 3D gain pattern of the waveguide slot array mounted on the aircraft.

IV. CONCLUSION

A general MoM-PO hybrid framework has been presented to fast and efficiently analyze complex antenna arrays mounted on extremely large-scale platforms. In this general hybrid MoM-PO framework, various types of onboard antenna arrays can be well handle by replacing the antenna array with a surrounding Huygens surface where the equivalent electric and magnetic currents are define. MoM equations are established on this Huygens surface and PO is employed to efficiently modelling the contribution of the extremely large platform. An iterative process is implemented to characterize the interaction between MoM-region and PO-region. To further reduce the peak memory usage and CPU time, AIM is applied to MoM-region to accelerate the solving of MoM equations. Numerical results show that the proposed general MoM-PO hybrid technique can dramatically reduce the consumption of computer memory and CPU time compared with the conventional MoM-PO method.

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