Engineering Analysis with Boundary Elements 73 (2016) 42–49

Contents lists available at ScienceDirect

Engineering Analysis with Boundary Elements

journal homepage: www.elsevier.com/locate/enganabound

Domain decomposition scheme with equivalence spheres for the analysis of aircraft arrays in a large-scale range

Ting Su [a], Mengmeng Li [a,b,*], Rushan Chen [a]

[a] Department of Communication Engineering, Nanjing University of Science and Technology, Nanjing, China
[b] State Key Laboratory of Millimeter Waves, Southeast University, Nanjing, China

ARTICLE INFO

Article history:
Received 19 May 2016
Received in revised form
29 August 2016
Accepted 31 August 2016

Keywords:
Equivalence theory
Integral equation
Multilevel fast multipole algorithm (MLFMA)

ABSTRACT

we propose a domain decomposition scheme for solving scattering problem from multi-objects distribution in a large-scale range. Each sub-object is enclosed by an equivalence sphere. The scheme is composed of the equivalence process and translation process. In the equivalence process, the scattering fields from the sub-object are produced by the equivalence mode currents on the equivalence sphere. The equivalence mode currents are the current expansion of the body of revolution (BoR) basis functions, which are transformed from the current expansion of the Rao–Wilton-Glisson (RWG) basis functions. The multilevel fast multipole algorithm (MLFMA) is employed to accelerate the equivalence process. In the translation process, the mode translation matrices are obtained based on the BoR basis functions and the coordinate conversion method for computing the interactions among the equivalence spheres. The adaptive cross algorithm (ACA) is used to accelerate the evaluation of mode translation matrices. The proposed approach is very efficient for analysis of the objects distributed in a large-scale range. Numerical results demonstrate that the approach provides significant improvements in terms of memory requirements.

1. Introduction

The multi-objects are random distributing in a large-scale range, such as aircraft fleet, multiple missile groups, etc. In the complicated electromagnetic environment, the sub-objects can be influenced by each other. The method of moments (MoM) accelerated by the multilevel fast multipole algorithm (MLFMA) [1–3] is preferred solution for this problem. The computation time and memory complexity of the MLFMA is $O(N \log N)$ [2]. In the MLFMA, the entire domain is enclosed by a proper size cube, and it is subdivided into sub-cubes hierarchically to obtain an oct-tree structure. Unfortunately, the multi-objects always distribute in a large-scale range, the entire computation domain will lead to the oct-tree with a lot of empty groups and large number of levels [4]. Therefore, the computation efficiency will be reduced significantly.

Recently, the domain decomposition method of integral equation (IE-DDM) has become a popular topic in CEM. The overlapped IE-DDM was proposed in [5]. A buffer region is required for each subdomain to keep the currents continuity between neighbor subdomains. In [6], the Robin type transmission conditions are used to enforce the continuity of the tangential fields on the touching surfaces, to obtain a non-overlapped IE-DDM. The equivalence principle algorithm (EPA) is another kind of the IE-DDM [7–12] The EPA is efficient for the analysis of multi-scale structures [9] and large scale arrays [12]. The method needs a proper equivalence surface to enclose the subdomains with fine structures. The original unknowns of the fine structures are transferred to the unknowns on the corresponding equivalence surface. The interactions among the objects are substituted by the interactions among the equivalence surfaces, accordingly. With this method, the number of unknowns of the new equation is reduced significantly when compared to the original one. Similar domain decomposition method based on equivalence is also proposed in [13–15].

There are some limitations of the existing EPA for standard scattering problems. Each subdomain enclosed by the equivalence surface cannot be electrically large, since the equivalence process involves the matrix inversion with the dimension of the number of unknowns inside the enclosed subdomain. Moreover, for targets with smooth surface, if the enclosed objects are meshed with Nyquist sampling size, e.g. 0.1 λ(λdenotes the wavelength), the number of unknowns on the equivalence surfaces will be larger than the original unknowns, thus it is worthless to use the EPA for these sub-objects. The macro basis functions are introduced in [15] on the equivalence surface to mitigate the computation burden.

* Corresponding author at: Department of Communication Engineering, Nanjing University of Science and Technology, Nanjing, China.
E-mail address: limengmeng@njust.edu.cn (M. Li).

http://dx.doi.org/10.1016/j.enganabound.2016.08.013
0955-7997/

It is well known that the MoM of body of revolution (BoR) is much efficient [16,17]. Only the generatrix of the BoR needs to be discretized. A Fourier series expansion in the angle of rotational symmetry reduces the problem to a system with independent Fourier modes [16]. The problem of the original three-dimensional problem is converted to a series of two-dimensional problems. However, the Fourier series expansion is only suitable for the structure of the BoRs share the same axis. In [18], the EPA is employed for analysis of the multiple BoRs scattering problems with axes arbitrarily oriented. The number of BoR basis functions on the equivalence sphere will be much smaller than the original RWG basis functions on the simulated multi-objects.

In this paper, the EPA based on the equivalence spheres is explored to multi-objects with arbitrary shape distributed in a large-scale range. The new contributions of this work are: 1) the method in [26] of the same authors is extended to aircraft arrays with the same structure, while the aircrafts can have different rotational angles. The equivalence scattering matrix will be evaluated only once, the coupling between two aircrafts can be computed effectively with BoR-MoM. 2)The equivalence process with sphere equivalence surface can obtain a pretty better precision than standard EPA [7,8] with block equivalence surface [26].

In Section 2-A, the equivalent currents expanded by RWG basis functions on the equivalence spheres are obtained by the equivalence process with the MLFMA acceleration. Then, the inner objects can be electrically large and each subdomain can share the same oct-tree and the feature of the identical sub-objects can be exploited. In Section 2-B, the bridge between the RWG currents coefficients and the BoR mode currents coefficients is established. The mode translation matrices for interactions among the equivalence spheres are given in Section 2-C. The adaptive cross algorithm (ACA) [19–23] is used to compress the mode translation matrices for reducing computing time and saving memory. The coordinate conversion method is used to maintain each couple equivalence spheres coaxial. Another benefit of the coordinate conversion method is the inner object enclosed in the equivalence sphere can be rotated with arbitrarily angle without recomputing the equivalence process and the mode translation matrices. The general formulation of the EPA based on equivalence spheres is given in Section 2-D. In Section 3, the numerical results are shown to demonstrate the accuracy and efficiency of the proposed scheme for solving the scattering from the large-scale multi-objects. A summary and conclusion are included in Section 4.

2. Theory

The scattering problem of multi-objects by the EPA based on equivalence spheres has been shown in Fig. 1. To simplify the problem, the perfect electric conductor (PEC) objects are considered. The scheme inherits the idea of the original EPA [7–9]. The difference is that the equivalence surfaces are fixed to be equivalence spheres denoted by ES_i, $i = 1, \ldots, N$. The range enclosed by an equivalence sphere is considered as one subdomain. i denotes the index of each subdomain and N denotes the overall number of subdomains. Γ_i denotes the exterior surface of each sub-object enclosed. The equivalence spheres and sub-objects enclosed are discretized by triangle patches for the RWG basis functions [1]. Meanwhile the generatrices of the equivalence spheres are discretized by line segments for the BoR basis functions [16].

The total processes of the proposed scheme in this paper can be decomposed into two components: the equivalence process and the translation process. The equivalence process is used to build the relationship between the incident equivalence currents and the scattering equivalence currents. The translation process is used to computing the interactions among the equivalence spheres. The details of the scheme are given as follows.

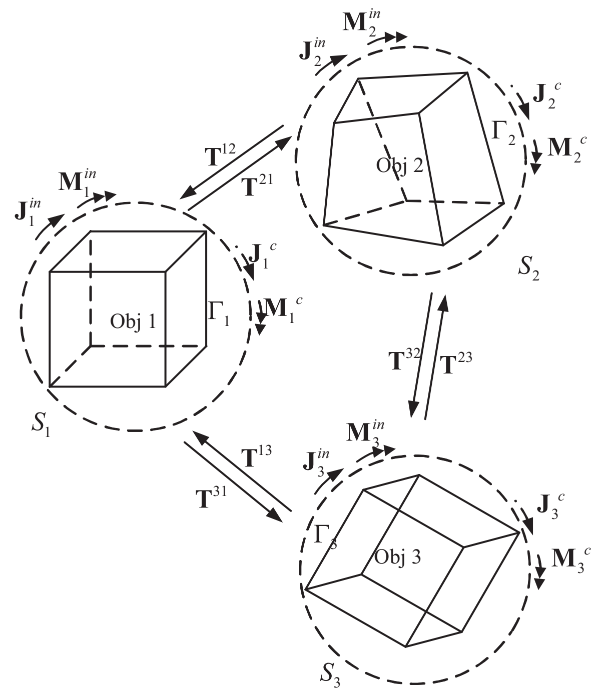

Fig. 1. The separated PEC objects enclosed by equivalence spheres.

2.1. The equivalence process accelerated by MLFMA

For the i_{th} subdomain, the equivalence process contains three steps: the equivalence incident currents on ES_i radiating into the inner object, determined by $\mathbf{Z}_i^{ph}$; the scattering from the inner objects solved by combination parameter of the combined field integral equation (CFIE), determined by $\left[\mathbf{Z}_i^{pp}\right]^{-1}$; the equivalence scattering currents on ES_i radiated by the inner scattering currents on Γ_i, determined by $\mathbf{Z}_i^{hp}$. Therefore, the equivalence process can be written as:

$$\begin{bmatrix}\mathbf{E}_i^{h,sca}\\ \mathbf{H}_i^{h,sca}\end{bmatrix} = \left[\mathbf{Z}_i^{hp}\right]\left[\mathbf{Z}_i^{pp}\right]^{-1}\left[\mathbf{Z}_i^{ph}\right]\begin{bmatrix}\mathbf{j}_i^{h,inc}\\ \mathbf{m}_i^{h,inc}\end{bmatrix} \tag{1}$$

where

$$\begin{aligned}\left[\mathbf{Z}_i^{ph}\right] &= \left[\gamma\mathbf{L}_i^{ph} - \eta(1-\gamma)\hat{n}_p \times \mathbf{K}_i^{ph} \quad \gamma\mathbf{K}_i^{ph} + \frac{1}{\eta}(1-\gamma)\hat{n}_p \times \mathbf{L}_i^{ph}\right]\\ \left[\mathbf{Z}_i^{pp}\right] &= \left[\gamma\mathbf{L}_i^{pp} + \eta(1-\gamma)\hat{n}_p \times \mathbf{K}_i^{pp}\right]\\ \left[\mathbf{Z}_i^{hp}\right] &= \begin{bmatrix}\mathbf{L}_i^{hp}\\ \mathbf{K}_i^{hp}\end{bmatrix}\end{aligned} \tag{2}$$

The superscript h denotes the surfaces ES_i and p denotes the surface Γ_i. $\hat{n}_p$ denotes the normal vector on the Γ_i toward outside. $\mathbf{j}_i^{h,inc}$ and $\mathbf{m}_i^{h,inc}$ denote the equivalence incident electric current coefficients and magnetic current coefficients expanded by RWG basis functions on the ES_i. $\mathbf{E}_i^{h,sca}$ and $\mathbf{H}_i^{h,sca}$ denote the vectors of the scattering electric fields and magnetic fields tested by the RWG basis functions on the ES_i, which is used to determine the equivalence mode scattering currents on the ES_i in next subsection. $\boldsymbol{L}$ and $\mathbf{K}$ denote the integral operator, and the detail of them can be found in [7]. γ is the combination parameter of the combined field integral equation (CFIE) [1] (ranges from 0 to 1) and η is the free-space impedance.