An Improved Domain Decomposition with Relaxation Method Used for Calculating Dynamic Characteristic of Electromagnetic Devices

Wenying Yang[1], Zilan Qiu[1], Fei Peng[1] and Guofu Zhai[1]
[1]School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin, 150001 China

Finite element method (FEM) is the mainstream tool to analyze the dynamic characteristics of electromagnetic apparatus. Parallel technology makes the computation of FEM more effective. For example, domain decomposition (DD) method is widely used to accelerate the FEM process. In the paper, a new finite element solution technique called nodal domain decomposition with relaxation (NDDR) is used to solve the dynamic characteristics of the electromagnetic device. The method can improve the parallelism to accelerate the dynamic characteristic solving. Moreover, We introduce Robin-type transmission condition to NDDR method to raise its solving efficiency.

***Index Terms*—Domain decompositon (DD), Dynamic characteristics, Electromagnetic apparatus, Finite element method (FEM), Parallel algorithm**

I. Introduction

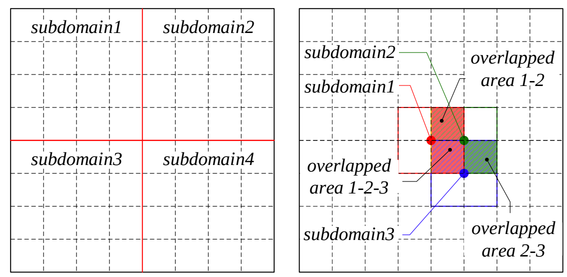
IN electromagnetic apparatus, electromagnets are often used to drive contacts separating. The dynamic characteristics determines the movement process of the electromagnetic device. Therefore, analysis of dynamic characteristics plays an important part in the design of electromagnetic apparatus [1].

In the computation of the dynamic characteristics, the electromagnetic field distribution is necessary to be calculated [2]. The finite element method (FEM) is widely used to calculate the electromagnetic field distribution. Many scholars have studied the acceleration of FEM process in electromagnetic field calculation. Recently, some scholars have proposed a new nodal domain decomposition with relaxation method (NDDR) for electromagnetic field parallel calculation, which has achieved excellent acceleration effect [3].

It is necessary to find a way to accelerate the solving process of dynamic characteristics. The NDDR method achieves a good acceleration effect in the calculation of the static electromagnetic field distribution. However, few scholars pay attention to its use in dynamic characteristic solving, although a large number of repeated FEM calculations are required in the solution of dynamic characteristics. Moreover, NDDR method's efficiency still has room for further improvement. In the paper, we apply the Robin type condition in the interface of two adjacent domains to speed up the convergence of NDDR method, and apply this method to accelerate the solution of the dynamic characteristics.

II. Improved Nodal Domain Decomposition With Relaxation Method

Both conventional domain decomposition (DD) method and NDDR method focus on accelerating the solution of FEM using parallel techniques. Conventional DD method is shown in Fig. 1(a), the whole solution domain is decomposed into several subdomains and processed separately by different cores of CPU. The fewer nodes and elements that each core is required to process, the higher solution efficiency can be obtained. Therefore, NDDR method was proposed, which contains only one node in a subdomain, as showed in Fig. 1(b). In this way, the degree of parallelism is greatly increased. In the case where the number of cores is sufficient, each core only needs to solve one node unit, and the solving efficiency can be significantly improved.



(a) Conventional DD method. (b) NDDR method

Fig. 1. Comparation between conventional DD method and NDDR method. This mesh domain contains 64 square elements and 49 inner nodes. (a) separate the domain to 4 subdomains, each subdomain contains many nodes and elements. (b) separate the domain to 64 subdomains, each subdomain contains only one node and there exists overlapped area between nearby subdomain.

Although NDDR method has achieved good acceleration in static electromagnetic field solving, its efficiency can still be improved. In the case study of NDDR method proposed by [3], thousands of GPU cores are used to solve the electromagnetic distribution, but the acceleration effect obtained is only tens of times. What's more, with the number of nodes increases, each core need to process multiple nodes, and the solution efficiency is further reduced.

In conventional DD method, using Robin-type transmission condition can obtain faster convergence speed than Dirichlet-type transmission condition [4]. Therefore, we introduce Robin-type transmission condition to NDDR method, to improve the solution efficiency of NDDR.

III. Dynamic Analysis With NDDR

To solve the dynamic characteristics of an electromagnetic device, we need to calculate differential equations to obtain the electromagnetic field distribution. It can be described as follows:

$$\begin{cases} \nabla \cdot A = B \\ \nabla \cdot (\upsilon \nabla A) = -J \end{cases} \tag{1}$$

where A is the magnetic filed potential vector, B is the magnetic field flux density, υ is the magnetic reluctivity and J is the current density.

Applying the Galerkin's method to each sub-network [5], a set of equations in the element can be obtained:

$$[S^e][A^e] = [F^e] \tag{2}$$

where $[S^e]$ relates to the node coordinates in the element, $[A^e]$ represents magnetic filed potential vector of each node and $[F^e]$ relates to the size of element and the current density in the element.

During the usual finite element solution process, each element needs to be assembled after element analysis. The finite element solution of the dynamic characteristics in this paper is achieved by improved NDDR method, which avoids the assembly process of the matrix and improves the efficiency of the solution through parallelization.

In the dynamic characteristic electromagnetic field solving process, the position of the armature in each time step is different, and the whole domain needs to be re-meshed and re-solved. Considering that the electromagnetic field at the same position does not change much, we can use the final value in the previous solution at the same position as the initial value of the next solution to achieve the iterative acceleration effect.

The differential equations of dynamic characteristics include circuit equations and motion equations:

$$\begin{cases} u = iR + \dfrac{d\psi}{dt} \\ m\dfrac{d^2x}{dt^2} = F - F_f \end{cases} \tag{3}$$

where u, i, R represent the voltage, current and resistance of the coil, ψ is the flux linkage, m is the mass of armature, F is the electromagnetic force and F_f is the load reaction force.

Converting (3) to the form of the first derivative equations as shown:

$$\begin{cases} \dfrac{di}{dt} = \dfrac{u - iR}{L} - \dfrac{i}{L}\dfrac{dL}{dt} \\ \dfrac{dv}{dt} = \dfrac{1}{m}(F - F_f) \\ \dfrac{dx}{dt} = v \end{cases} \tag{4}$$

where L is the magnetic system inductance.

The flowchart of the solution is shown in Fig. 2. The difference equation in this process can be solved by fourth-order Runge-Kutta method.

IV. Case Study

To verify the NDDR method can accelerate the solution of electromagnetic dynamic characteristic, a dynamic model of the improved solenoid contactor is proposed to be calculated, which is shown in Fig. 3. Comparing with conventional

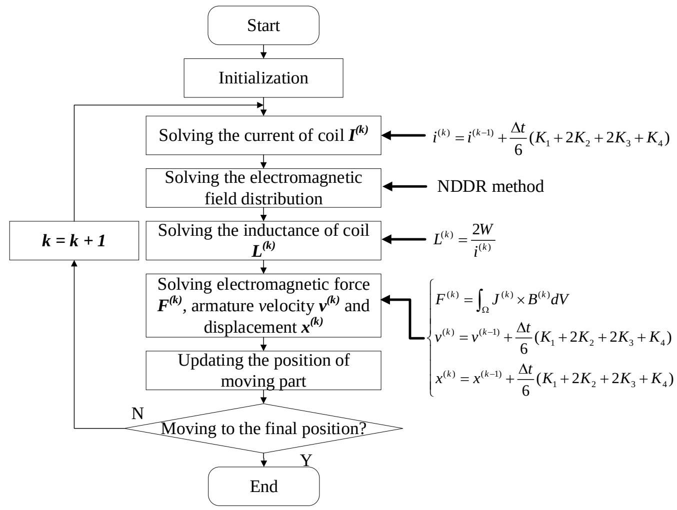


Fig. 2. Dynamic solving process with NDDR. In fourth-order Runge-Kutta expression, K_p is associated with (4).

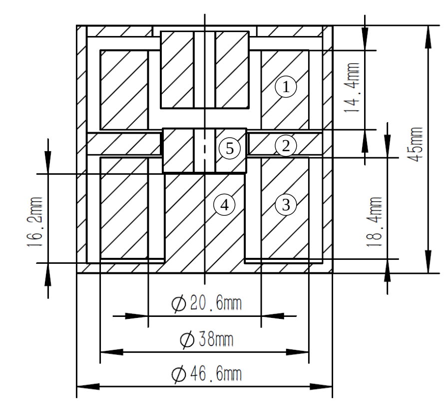


Fig. 3. Structure of solenoid contactor (1-Top coil, 2-Permanent magnet, 3-Bottom coil, 4-Iron core, 5-Armature).

solenoid contactor, this model combines solenoid with permanent as its operator structure.

Many factors will influence the speedup and accuracy of the improved NDDR method, such as number of nodes, number of cores and relative tolerance. In extended paper, we will discuss the influences of different factors and compare the speedup and accuracy of the solution result with COMSOL Multiphysics'.

References

[1] S.- Wang, T. Miyanao, and M. Hubbard, "Electromagnetic field analysis and dynamic simulation of a two-valve solenoid actuator," IEEE Transactions on Magnetics, vol. 29, no. 2, pp. 1741–1746, Mar. 1993.

[2] Y. Jiaxin, L. Huimin, M. Guangcheng, C. Shuqing, and C. Zhaowen, "Research on the dynamic calculation model for a dc solenoid electromagnetic contactor and its contact characteristics in break process," in 2015 IEEE 61st Holm Conference on Electrical Contacts (Holm), 2015, pp. 191–194.

[3] P. Liu and V. Dinavahi,"Matrix-Free Nodal Domain Decomposition With Relaxation For Massively Parallel Finite-Element Computation of EM Apparatus," IEEE Transactions on Magnetics, vol. 54, no. 9, pp. 1–7, Sep. 2018.

[4] J. Douglas and C.-S. Huang, "An accelerated domain decomposition procedure based on robin transmission conditions," BIT Numerical Mathematics, vol. 37, no. 3, pp. 678–686, 1997.

[5] Rao, S. S . "The Finite Element Method in Engineering," Pergamon Press, 1982, pp. 194-198.