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

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Finite element method (FEM) is necessary to analyze the dynamic characteristics of electromagnetic mechanisms. Parallel technology makes the computation of FEM more effective. For example, domain decomposition (DD) method is widely used to accelerate the FEM process. In this 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. This method can improve the parallelism to accelerate the dynamic characteristic solving. We introduce Robin-type transmission condition to NDDR method, which can greatly improve the solving efficiency of it.

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

I. Introduction

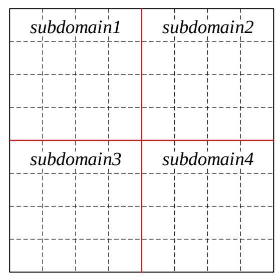
In electromagnetic apparatus, electromagnetic devices are often used to drive contact separating or other load work. Although the static simulation is usually performed to judge the characteristic of the electromagnetic device in engineering, it is the dynamic characteristic that determines the movement 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 characteristic, the electromagnetic field distribution is necessary to be calculated when the armature moves at different positions [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. 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].

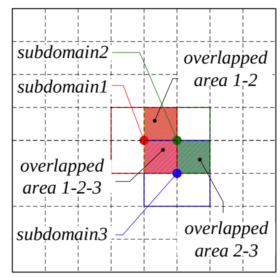
The computation of dynamic characteristic always consumes a lot of computing resources, so it is necessary to find a way to accelerate the solving process. The NDDR method achieves a good acceleration effect in the calculation of the static electromagnetic field distribution, which means it can also be applied to dynamic characteristic solving. However, few scholars pay attention to its use in dynamic characteristic solving. What's more, NDDR method's efficiency can to be greatly improved. In this paper, we apply the Robin type condition in the interface of two adjacent domains to improve the convergence speed of NDDR method, and apply this method to accelerate the solution of the dynamic characteristic.

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 obtain. Therefore, NDDR method proposes an extreme idea, which means 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 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 characteristic of an electromagnetic device, we need to calculate differential equations for electromagnetic field distribution. The solution of the electromagnetic field distribution is consistent with the solution of the static magnetic field. The differential equations of the electromagnetic field are solved by FEM. 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 induction, υ is the magnetic permeability and J is the current density.

After each sub-network are discredited by Galerkin's method [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 $[F^e]$ relate sto 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. Then we need to solve a nonlinear large sparse symmetric positive definite (SPD) system. The finite element solution of the dynamic characteristic 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 resolved. 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.

To simplify the solving process, 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.

In this paper, we use the weak coupling method to solve the dynamic characteristics of the electromagnetic system. The

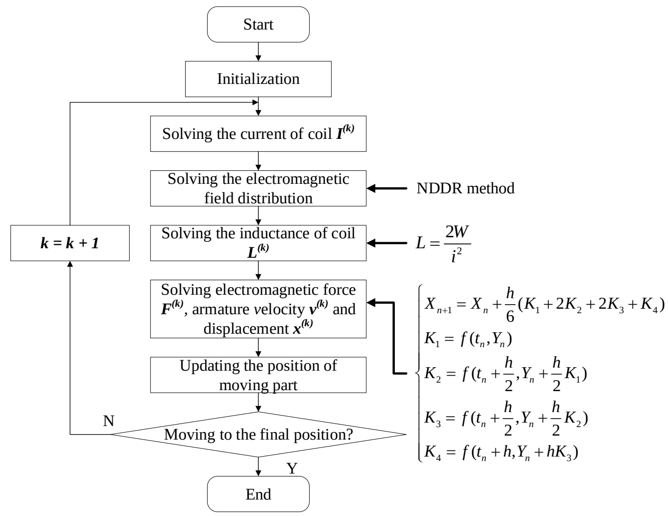


Fig. 2. Dynamic solving process with NDDR

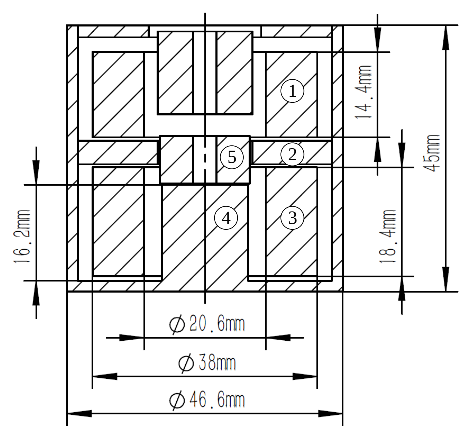


Fig. 3. Structure of solenoid contactor (1-Top coil, 2-Permanent magnet, 3-Bottom coil, 4-Iron core, 5-Armature).

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

IV. Case Study

In order to verify that the NDDR method can accelerate the solution of electromagnetic dynamic characteristic, this paper uses a dynamic model of the improved solenoid contactor to calculate. Comparing with common solenoid contactor, this model combines solenoid with permanent as its operator structure, as showed in Fig. 3. Finally, we compare the speedup and accuracy of this solution result with the COMSOL Multiphysics' solution result.

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.