Parallel Solving of 3D Eddy Current Losses in Large Transformer Based on Element by Element Method

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The graphic processing unit (GPU) acceleration of 3D eddy current losses calculation by parallelizing the element by element (EBE) finite element method (FEM) is proposed in the paper. Two distinctive characteristics of EbE method included, one is not to assemble the system matrix and the other is inherent parallel nature. So we can fulfill the parallelism directly on the elements level based on the GPU platform. Considering the ill-conditioned character of 3D eddy current problem, a novel preconditioner named generalized Jacobi (GJ) is used to accelerate the conjugate gradient (CG) iterative solution scheme. A large power transformer is taken as an example to compute the eddy current losses distribution to validate the proposed method, the numerical experiments is carried out on the GPU platform.

***Index Terms*—Element by element method, generalized Jacobi precondtioner, compute unified device architecture, 3D eddy current problem.**

I. Introduction

PARALLEL ALGORITHM is always the research hotspot in eddy current computing field. The parallel methods for finite element analysis mainly include the parallel solution of FE equations, domain decomposition method, and the parallel algorithm based on element level, i.e., Element by Element (EBE) parallel FE method [1].

The EBE FEM based is an effective method to improve the degree of parallelism at the algorithm-level. With this method the main calculation can be performed independently and parallel for each element, and only in limited stages the correlation and transmission of the element data should be carried out. Therefore, it doesn't need to create and store the global coefficient matrix, thus the requirement of memory is reduced greatly. The larger of the computational scale, the higher efficiency of EBE method can be got. So that EbE method is especially suitable for the numerical computation of engineering electromagnetic field problems with complicate structure and huge computational scale. At present the research of EbE method is developing to a stage of combining of algorithm, software and hardware. In recent years, based on the Graphic Processing Units (GPU)[2]-[6], the General Purpose Computation on GPUs (GPGPU) has developed rapidly. Furthermore, the arising of the Compute Unified Device Architecture (CUDA) supplies a reliable programming environment for the realization of the GPGPU, which provides a certain condition for the parallel computation of large-scale engineering problems.

For the 3D eddy current problem, the coefficient matrix of the resultant FEM equations is ill-conditioned. In this case if the CG method is still used to solve the equations, the convergence performance will get worse greatly, or even a stable solution can not be obtained. And the traditional efficient preconditioned method such as incomplete Cholesky conjugate gradient (ICCG) solver will be inefficient for EbE FE method. So the new preconditioner which can be used together with EBE method and validity for 3D ill conditioned problem is needed.

Transformer is served as main equipment in the power system, it has great significance for improving the reliability operation and ensuring the safety operation to calculate eddy current losses and distribution, so that to avoid local overheating in the structure. However, due to the asymmetry of the physical model of actual equipment, the numerical simulation has to be carried out on the whole model and large computer resource is needed. Both the present computer hardware and software are unable to meet the requirements of rapid and effect computing. This paper proposed a parallel computing method and parallel computing platform to resolve the contradictions among of computational scale, computational speed and computational accuracy of large-scale three-dimension engineering eddy current problem

In author's previous work[7]-[9], the standard Jacobi (SJ) preconditioned method which can be implemented by EBE method has been used to parallel solving 2D eddy current problem and 3D linear eddy current problem (TEAM workshop 7). However, for the 3D eddy current losses calculation in large power transformer (shown in Fig.1), solving domain contain ferromagnetic material, and this will result in Jacobi preconditioned method becoming inefficient. This paper presents a robust generalized Jacobi (GJ)[10] preconditioner to accelerate the convergence speed.

II. EbE CG Method

As all we known, CG method mainly contains two type inner product calculations, i.e., $(\boldsymbol{r},\boldsymbol{r})$ and $(\boldsymbol{p},\boldsymbol{Ap})$ which can be calculated by EbE method as follows:

$$(\boldsymbol{r},\boldsymbol{r}) = \boldsymbol{r}^T\boldsymbol{r} = (\boldsymbol{r}^e)^T\boldsymbol{Q}\boldsymbol{Q}^T\boldsymbol{r}^e = \sum(\boldsymbol{r}^e)^T\boldsymbol{r}^{(e)} \tag{1}$$

where $\boldsymbol{r}^{(e)} = \boldsymbol{r}^e \oplus \sum_{j\in adj(e)} \boldsymbol{r}^j$, $\boldsymbol{r}$ is global residual, $\boldsymbol{r}^e$ is local element residual, $\boldsymbol{Q}$ is the connection matrix(CM).

$$\begin{aligned}(\boldsymbol{p},\boldsymbol{Ap}) &= \boldsymbol{p}^T\boldsymbol{Ap} = \boldsymbol{p}^T\boldsymbol{Q}^T\boldsymbol{A}^e\boldsymbol{Qp}\\ &= (\boldsymbol{Qp})^T\boldsymbol{A}^e(\boldsymbol{Qp}) = (\boldsymbol{p}^{(e)})^T\boldsymbol{A}^e\boldsymbol{p}^{(e)}\end{aligned} \tag{2}$$

Equation (1) and (2) show that the EbE-CG method can be fulfilled totally on elements level and solved parallelly on GPU.

III. General Jacobi Preconditioner

For the calculation of 3D eddy current filed in larger power transformer, due to the solving domain contains ferromagnetic material, the solving equations appear to be ill-conditioned symmetric indefinite. So it is crucial to research an efficient preconditioned method. The difference of conductivity and permeability between eddy current filed and non eddy current filed is the mainly reason that caused ill-conditioned characteristic. In this paper, an efficient and suitable for parallel computing called GJ preconditoner is adopted. More important, the GJ preconditoner can be formed, inverted, and implemented within an 'element by element' framework as readily as standard Jacobi(SJ) preconditoner [3]. It was derived from SJ perconditioner, so it is convenient for parallel computing. The GJ preconditioner can be given as

$$P_{GJ}^{(e)} = \begin{bmatrix} diag\left(k_{jdiag}^{(e)}\right) & 0 \\ 0 & diag\left(P_{G\varphi}^{(e)}\right) \end{bmatrix} \quad (3)$$

where, $diag(\cdot)$ is the diagonal entry of diagonal matrix, and φ is electric scalar potential. All the elements in (3) are referenced in globally. Furthermore, the calculation process of $P_{G\varphi}$ is as below

$$P_{G\varphi}^{(e)} = \frac{\left[k_{jxj\varphi}^{(e)}\right]^2}{k_{jxjx}^{(e)}} + \frac{\left[k_{jyj\varphi}^{(e)}\right]^2}{k_{jyjy}^{(e)}} + \frac{\left[k_{jzj\varphi}^{(e)}\right]^2}{k_{jzjz}^{(e)}} - k_{j\varphi j\varphi}^{(e)} \quad (4)$$

From (3) and (4), we can see that GJ preconditioned method is consist of element value. It is still a high paralleled preconditioned method as SJ. The aim of GJ is mainly to deal with coefficient that corresponding to φ .

IV. Numerical Experiment

In this paper, a single power transformer with 28.333MVA230kV (shown in Fig.1) is used to calculate the eddy current losses in structure.

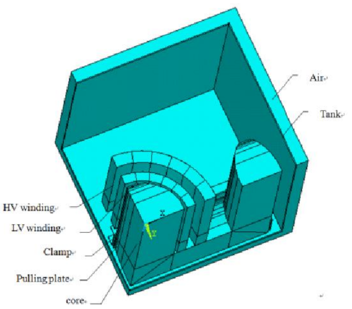

Fig.1 The one-eight model of single phase power transformer.

The numerical computations are carried out on a server with NVIDIA GTX 660 GPU clocked at 1.0 GHz with 960 cores and 2G DDR5 global memory, and an CPU with Intel Xeon E3-1230 CPU 3.3 GHz with 8G global memory. All the programming is in C++ language, and compiled by Visual Studio 2013 and CUDA 7.5

The part of numerical results is shown in Table I.

TABLE I
Speed up rate of numerical experiment

Iteration method	Convergence criteria	CPU time(h)	GPU time(h)	Speed up rate
EBE-JPCG	3.752e-8	Non convergence	-	-
EBE-GJPCG	3.752e-8	3.32	2.36	1.4

V. Conclusions

The GPU and EBE method applied to 3D eddy linear eddy current calculation of large power transformer is main contributions of this work. And GJ preconditioner is another significant contribution. GJ preconditioned method is efficient for solving 3D eddy linear eddy current problem which is ill-conditioned. The detailed results including the distribution of eddy current on the tank surface will be given in the extended paper.

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