Parallel Algorithm for Electromagnetic Field Computation Based on Particle Simulation Algorithm

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Abstract. Based on current serial algorithms for electromagnetic field computation, the parallel algorithm concept where the “divide and conquer” approach is adopted has designed and implemented electromagnetic field computation in 3D rectangular coordinates, cylindrical coordinates and polar coordinates of CHIPIC software. The speedup ratio of the parallel algorithm is analyzed. Finally, the correctness and efficiency of the algorithm are verified through case studies.

Keywords: Electromagnetic Field Computation, FDTD, Parallel Algorithm, Speedup Ratio

1. Introduction
Plasma is a complex system of charged particles with collective motion characteristics. Plasma often behaves as a complex nonlinear behavior. It is difficult to analyze it accurately by traditional theoretical and experimental research methods. In the 1950s, with the development of computer technology, a new research method, computer numerical simulation, began to be used in the study of plasma. The traditional plasma numerical simulation research generally uses the hydrodynamics simulation or the dynamics simulation, regardless of the fluid equation or the dynamics equation, when establishes has made the smooth approximation to the plasma which is the statistical system, has erased their intrinsic statistical fluctuation effect, but these fluctuation effects may develop into the important physics like the turbulence under the certain condition Phenomenon. Based on the message passing model, there are mainly two parallel computing strategies of electromagnetic particle simulation[1-3]. A parallel computing strategy is to distribute the particles evenly to each computing process, and assign the amount related to the grid to all processes, so that the particle propulsion solution, the update of charge density and current density are completely parallel, then the charge density and current density obtained by each process are accumulated, and finally each process separately solves the electromagnetic field of all grids. The advantage of this parallel strategy is process load balancing, and the disadvantage is that there is a huge amount of communication between processes, and each process computes the electromagnetic field of all grids, and the amount of repeated calculation is large. Another parallel computing strategy is to divide the physical model into multiple regions according to space, and the electromagnetic field updating and particle propulsion solution in each region are completed by the same process. When the process is solving the electromagnetic field and particle propulsion in the region, it needs to call the message transfer function to obtain the necessary boundary information from the adjacent region, so as to ensure the
correctness of parallel computing. The outstanding advantage of this parallel computing strategy is that the amount of communication between processes is greatly reduced, and the amount of repeated computing is very small. The disadvantage is that the number of particles in each region may vary greatly, which makes the load of each process unbalanced.

CHIPIC software is an electromagnetic particle simulation algorithm based on the finite-difference time-domain algorithm and PIC (particle in cell) method, which is mainly used in the design and research of high-power microwave devices. In the 3D particle simulation, especially for large-scale devices and terahertz microwave sources, it needs a very long computing time, and it is difficult to achieve with a single computer. Parallel computing is one of the most effective ways to solve the computing time. In this paper, firstly, through the analysis of the features of the serial algorithm for electromagnetic field computation of CHIPIC software, the parallel algorithm of the electromagnetic field is designed, and the parallel speedup ratio is analyzed. Finally, the algorithm is tested and verified in the LAN of the laboratory\textsuperscript{[4-6]}.

2. Serial algorithm for electromagnetic field computation

The change of electromagnetic field satisfies the Maxwell equations:

\[
\begin{align*}
\nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t}, \nabla \cdot \vec{D} = \rho \\
\nabla \times \vec{H} &= \vec{J} + \frac{\partial \vec{D}}{\partial t}, \nabla \cdot \vec{B} = 0
\end{align*}
\]

(1)

In addition, the following relationships are observed:

\[
\begin{align*}
\vec{D} &= \varepsilon \vec{E} = \varepsilon_r \varepsilon_0 \vec{E} \\
\vec{B} &= \mu \vec{H} = \mu_r \mu_0 \vec{H}
\end{align*}
\]

(2)

Where \(\vec{E}\) represents the electric field strength, \(\vec{B}\) represents the magnetic induction intensity, \(\vec{H}\) represents the intensity of the magnetic field, \(\vec{J}\) represents the current density, \(\vec{D}\) represents the potential shift-vector.

\(P\) represents the charge density, \(\varepsilon\) represents the capacitance of the medium, \(\varepsilon_r\) represents the relative capacitance, \(\varepsilon_0\) represents the vacuum capacitance, \(\mu\) represents permeability, \(\mu_r\) represents the relative permeability, \(\mu_0\) represents the vacuum permeability. In the software, the magnetic medium is not considered, i.e., \(\vec{B}=\mu_0 \vec{H}\), for the relative dielectric capacity \(\varepsilon_r\), only the following is considered:

\[
\varepsilon_r = \begin{bmatrix}
\varepsilon_r & 0 & 0 \\
0 & \varepsilon_r & 0 \\
0 & 0 & \varepsilon_r
\end{bmatrix}
\]

(3)

In the computation of 3D electromagnetic field, different formats of the polar coordinate system \((R, \varphi, Z)\) are the same as those in the cylindrical coordinate system \((Z, R, \varphi)\). However, in the actual program processing of CHIPIC software, the processing orders of various components in the electric and magnetic fields are different.

3. Parallel algorithm for electromagnetic field computation

Parallel computing is to use parallel computers to reduce the time needed to solve a single problem. Now, parallel computing has become a standard method to solve scientific and engineering problems in various fields, such as controllable thermonuclear fusion, space physics, weather forecast, aircraft design, biopharmaceutical, petroleum exploration, etc. Parallel computer is a multiprocessor computer system supporting parallel computing. Contemporary parallel computer architecture mainly includes: parallel vector processor (PVP), symmetric shared memory multiprocessor (SMP), distributed shared memory parallel machine (DSM), large-scale parallel processor (MPP) and workstation cluster (cow) O parallel algorithm, which is to solve problems and process data on various parallel computers. Its
essence is to map multitasking to multiprocessor for execution, or The real multidimensional problem is mapped to a multiprocessor with a specific topology. At present, the commonly used parallel algorithm design technologies include: divide and conquer strategy, pipeline technology, balance tree technology, multiplication technology and acceleration cascade strategy. The design of parallel algorithm can be directly based on the specific parallel computer, or based on the parallel programming model.

From the analysis of the serial algorithm, it can be seen that the computation formulas of electric and magnetic field components can be written in a unified form in a rectangular coordinate system, cylindrical coordinate system, and rectangular coordinate system. Therefore, as long as the parallel computation is realized in a rectangular coordinate system, the parallel computation in a cylindrical coordinate system and a polar coordinate system is implemented simultaneously. However, the molecular region is delimited along Z direction in rectangular coordinate system and polar coordinate system, and the cylindrical coordinate system delimits the molecular region along the direction of \( \varphi \). Assume that the time required for serial computation of each time step is \( T_i \). There are \( n \) processes in parallel computing, and the time for each time step to transfer boundary field information is \( T \). The time required for each time step in parallel computing is \( T_p \approx T_i / N + T_i \). As the time steps of the iteration of serial computation and parallel computation are equal, the speedup ratio can be obtained as follows:

\[
\psi = \frac{T_i}{T_p} = N \left( 1 - \frac{NT_i}{T_i + NT_i} \right) \tag{4}
\]

Equation (4) shows that the smaller the ratio of \( T_i \) to \( NT_i \), the higher the speedup ratio, and the main factors influencing the ratio of \( T_i \) to \( NT_i \) include: (a) the more the number of grids along the sub-area division direction, the more the number of iterative computation grids needed for each process, the closer the speedup ratio is to the number of processes; (b) the processor computing power, the ability of computer network to transmit information, the higher the information transmission rate between computers relative to the processor computing power, the closer the speedup ratio is to the number of processes.

4. **Experimental results**

The parallel algorithm is tested in a local area network composed of six computers. The results show that the parallel computation results are consistent with the serial computation results, and have a better speedup ratio and efficiency. The test results of electromagnetic wave propagation in rectangular waveguide in rectangular coordinate system and cylindrical waveguide in polar coordinate system are listed below.

Tables 1 and 2 show the simulation time, speedup ratio, and efficiency of different network and process numbers of rectangular waveguide (rectangular coordinate). The diagram of speedup ratio and efficiency changing with the number of processes is shown in Figures 1 and 2, respectively.

**Table 1.** Simulation time of different grid number and process number (\( P \) is process number)

| Grid number (X×Y×Z) | Simulation computation time/s |
|---------------------|------------------------------|
|                     | P=1                          | P=2  | P=3  | P=4  | P=6  |
| 50×50×200           | 701                          | 388  | 281  | 230  | 198  |
| 50×50×300           | 1141                         | 617  | 439  | 355  | 264  |
| 100×50×300          | 2569                         | 1384 | 999  | 787  | 580  |
Table 2. Speedup ratio and efficiency of different grid number and process number

| Grid number (X×Y×Z) | P=2 |   | P=3 |   | P=4 |   | P=6 |   |
|---------------------|-----|---|-----|---|-----|---|-----|---|
|                     | ψ   | η | ψ   | η | ψ   | η | ψ   | η |
| 50×50×200           | 1.81| 0.90 | 2.49| 0.83 | 3.05| 0.76 | 3.54| 0.59 |
| 50×50×300           | 1.85| 0.92 | 2.60| 0.87 | 3.21| 0.80 | 4.32| 0.72 |
| 100×50×300          | 1.86| 0.93 | 2.57| 0.86 | 3.26| 0.82 | 4.43| 0.74 |

Figure 1. Schematic diagram of the speedup ratio variation with process number

Figure 2 shows the input power curve. It can be seen that in the initial stage, the input power gradually increases from 0 due to the rising edge of the voltage; after the cathode emits electrons, the anode and cathode are broken down, and the input power begins to decline; finally, a stable electronic spoke and microwave output will be formed, and the input power will remain stable; the input power after stabilization is about 27.5 GW.

Figure 2. Input power curve

The experimental results suggest that when the number of grids perpendicular to the sub-region is the same, the more grids along the sub-region, the higher the speedup ratio and efficiency. When the number of grids perpendicular to the sub-region is the same, the communication cost of each time step is the same. The more grids along the sub-region are divided, the less the communication cost is relative to the computation and the higher the efficiency is. When the number of grids perpendicular to the sub-area is the same, and the number of grids along the sub-area is the same, the efficiency decreases with the increase of the number of processes. Because of the increase of the number of
processes, the additional communication overhead will inevitably lead to the decrease of efficiency. In addition, when the number of grids along the sub-region division direction is constant, and the number of grids perpendicular to the sub-region division direction increases with the same number of processes, the speedup ratio, and efficiency also slightly increase. Because when the number of grids in the direction perpendicular to the sub-area partition increases, although the computation and communication amount increase in equal proportion, the time of sending data is composed of start-up time and transmission time, and the start-up time will not change, so that the ratio of the increased communication time of each process to the original communication time is smaller than the ratio of the increased computation time to the original computation time.

5. Conclusion
A parallel algorithm of three-dimensional electromagnetic particle simulation based on particle simulation algorithm chip is established. The advance of three-dimensional electromagnetic particle simulation in each time step is abstracted into three calculation processes: electromagnetic field renewal process, particle advance solution process, charge density and current density renewal process; based on particle simulation algorithm chip, the parallel calculation method of each calculation process is designed respectively; and the algorithm is tested and analyzed on multi-core computer. This paper studies the parallel computation based on particle simulation algorithm chip, and points out the programming method of 3D parallel electromagnetic particle simulation program based on MPI / OpenMP mixed mode. The test results show that the research has achieved better acceleration ratio and efficiency, which lays a solid foundation for the future parallel computing of the whole particle simulation.

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