The Research of Parallel Computing for Large-scale Finite Element Model of Wheel/Rail Rolling Contact

Xiao Qian
Railway Science and Technology Research and Development Center China Academy of Railway Sciences Beijing, China

Wang Chengguo
Railway Science and Technology Research and Development Center China Academy of Railway Sciences Beijing, China
wangchengguo@rails.com.cn

Guo Ge
Institute of Computing Technologies China Academy of Railway Sciences Beijing China.
gougelulu@gmail.com

Abstract- With the development of computer technology and calculation methods, the finite element method to analyze wheel/rail rolling contact became popular. For the increasing requirement of calculation scale and computing accuracy, the parallel computing method and parallel computing environment become an effective way to solve this problem. The parallel computing methods of contact problem is analyzed firstly. Then, the contact algorithm and parallel computing of ABAQUS is introduced. And the parallel computing environment using MPI in ABAQUS is put forward. On the basis of cluster, some different finite element model is solved by implicit and explicit solution. It is found that the mesh size of wheel/rail contact field is refined to 0.75mm in order to ensure accuracy for engineering. At last, the parallel computing for the contact problem of wheel/rail is discussed using the speedup and efficiency.

Keywords-Wheel/Rail Rolling Contact, Large-scale Finite Element(FE) Model, Cluster, Parallel Computing

I. INTRODUCTION

In recent years, many scholars carried out elastic-plastic analysis, creep-adhesion analysis, wear analysis and fatigue and crack analysis of wheel/rail rolling contact by using finite element method. However, there was no discussion about the calculation accuracy of FE model in the existing analysis. Wheel/rail rolling contact is a typical nonlinear problem, and it is the base of kinds of wheel/rail rolling analysis for more than ten tons or even tens of tons of on a small contact area. So a large-scale finite element model to ensure the analysis accuracy of wheel/rail rolling contact is particularly important. And this method put forward new demands for calculation and computer. With the emergence and the rapid development of high-speed information networks, network parallel computing become a major direction. It has enormous calculation potential, good cost-performance ratio, extendibility and flexible construction, which can analyze large-scale FE model of complex structures [1].

II. THE FINITE ELEMENT CONTACT PROBLEM PARALLEL ALGORITHM

Contact algorithm includes contact search algorithm and the contact-force algorithm. Contact search algorithm is designed to identify which units in the calculation domain being in the contact state. The contact force algorithm is to allow configuration of the system to meet the non-penetration constraints of contact boundary. These two algorithms are available for parallel calculation through the domain decomposition [2]

The basic idea of FE parallel computing is to achieve the FE mesh, and then decompose the entire domain into p sub-domains, \( \Omega_1, \Omega_2, \ldots, \Omega_p \) shown in Figure 1:

![Figure 1. Domain decomposition map](image)

According to finite element theory, the total stiffness matrix of sub-domain \( \mathbf{K}_{i} = \mathbf{K}_{ijkl} \mathbf{u}_{ijkl} \), ‘U’ for the stiffness matrix assembly process; \( \mathbf{K}_{ijkl} \) as a unit stiffness matrix; \( n_{i} \) as the number of sub-domain \( \Omega_i \).

The total stiffness matrix of whole domain is \( \mathbf{K} = \mathbf{K}_{ijkl} \mathbf{u}_{ijkl} \).

It can be seen that the finite element model is to be divided into several sub-domains with domain decomposition and these theses domains is mapped on different processors to concurrently carry out finite element analysis. The quality matrix and stiffness of are assembled on the host processor finally. Most of finite element analysis software achieves parallel computation with domain decomposition method.

III. ABAQUS CONTACT ALGORITHM AND PARALLEL COMPUTING

ABAQUS is powerful non-linear finite element analysis software, which is capable of simulating highly nonlinear problems and is very convenient to solve the contact...
problem in particular. ABAQUS / Standard and ABAQUS / Explicit are two solvers and can simulate contact problem. But there some differences in analog functions and contact algorithm. The contact algorithm in ABAQUS / Standard is based on Newton-Raphson, which check all contact state to determine whether a subordinate node is open or closed in the beginning of each incremental step. There is no iteration to solving nonlinear problems in ABAQUS / Explicit. The equation is explicitly solved by mechanical state of a previous incremental step [3].

It is not uncommon that some large-scale FE model with more than 10 million degrees of freedom needs to deal with. For those models, it is difficult to get a result of analysis within a reasonable time, not to mention the repeated debugging and optimization. With the development of parallel finite element analysis, the parallel computing of ABAQUS become more sophisticated. It supports two parallel modes of Threads and MPI. Threads mode can run only in the SMP (Symmetric Multi-Processing) system, while the MPI (Message Passing Interface) mode can both run in the SMP and network cluster. The parallel solver of ABAQUS / Standard includes parallel direct sparse matrix solver of dynamic load balancing function, the parallel iterative solver based on the domain decomposition and Lanczos eigenvalue solver. The parallel solver of ABAQUS / Explicit is also based on domain decomposition.

IV. THE CONSTRUCTION OF PARALLEL PLATFORM WITH NETWORK CLUSTER

Parallel computing in ABAQUS is realized by cluster computing environment with MPI criterion. Cluster computing environment consists of the management node, computing nodes, network, storage, monitoring and software. The management node provide user interactive interface to receive user’s computing tasks, assign task decomposed to each compute node and obtain results from the calculation nodes. The final summary result from all the calculation results of each computing nodes is stored in the storage device. The parallel environment of network cluster is built according to the following project. The HP CP3000 cluster platform, H3C S5120-EI Gigabit Ethernet switch, Huasai Oceanspace N8000 storage array and other equipment is selected. The logical structure of cluster is shown in Figure 2. It is consist of 12 computing nodes and a management node. Computing nodes is configured with two 4core E5520 processors, 8G DDR3 memory and HP Proliant BL280c G6 blade servers with 146G SAS interface. The configuration of management node is same to computing nodes. A virtual channel between management node and network storage is established through the virtual Link configuration of switch. The historical computing tasks and results of analysis are saved in Network memory array.

The 64-bit Linux operating system is installed in management node and computing nodes in cluster. At each node, the parallel computing software of HP-MPI 2.20, respectively and the cluster management tool of HP CMU are installed. The communication between management node and computing nodes, as well as between user and management node is established through the SSH channel. Finally, the finite element analysis software, ABAQUS6.9 is installed in management node and the parallel environment parameter is configured.

V. CASE OF WHEEL-RAIL ROLLING CONTACT CALCULATION

A. Static analysis of wheel/rail rolling contact with the implicit calculation

The refined mesh is one of the principal means to ensure calculation accuracy. The FE model of wheel/rail rolling contact is refined just to wheel/rail contact area for the coordination of local calculation accuracy and computational efficiency. The degree of local refined mesh has a direct impact on the size of finite element model. Figure 3 shows the FE model of static wheel/rail contact as an example, when the size of contact area’s mesh diminish by 4mm, 2mm, 1.25mm, 1mm, 0.75mm to 0.5mm, the entire size of the FE model have a sharp rise. And computer’s performance requirements are very high, as shown in Table 1. When the size of contact area mesh is 1mm, the number of element is 666,544 and the memory requirement of computer s is almost 24G. So it is difficult to meet the computing requirements for alone computer, parallel computing must be taken to complete a large-scale fine finite element model.

<table>
<thead>
<tr>
<th>Size of contact mesh</th>
<th>4mm</th>
<th>2mm</th>
<th>1.25mm</th>
<th>1mm</th>
<th>0.75mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of element</td>
<td>69160</td>
<td>212026</td>
<td>327896</td>
<td>666544</td>
<td>1010160</td>
</tr>
</tbody>
</table>

![Figure 2. Logical Structure of Cluster](image)

![Figure 3. The FE model of wheel/rail rolling contact for static analysis](image)
The different sizes of FE model of wheel/rail rolling contact, which the diameter of wheel is 840mm, the rail cant is 1/20 and axle load is 15T, is computed by using network cluster with 12 nodes based on MPI. The specific value of maximum Mises stress, maximum contact stress and area of contact patch are shown in Table II. Figure 4 shows the calculation results when the size of contact area mesh is 1mm for large-scale FE model.

If the difference of two adjoining analysis results is less than 2%, it indicate that the current mesh density and element type are sufficient to assure the analysis accuracy [4]. So the mesh size of contact area of wheel/rail refined to 0.75mm can ensure the accuracy requirement of engineering analysis.

The calculation speed of implicit algorithm is decided by the computer's memory. Multi-node network cluster can calculate the large-scale finite element model. But not with the number of nodes is increased, the computing time is reduced proportionally. Figure 5 shows the relationship between computing time and number of nodes for a large-scale FE model of wheel/rail contact. From the graph, we can see that alone computer can’t calculate the large-scale FE model of contact area refined to 0.75mm; the task is done by using 2 nodes while the computing time is long; the time-consuming is decreased sharply using 4 nodes and the computing efficiency isn’t effective improve when the nodes is continually increased.

### Table II. The Calculation Results of Different Size of FE Model

<table>
<thead>
<tr>
<th>Size of contact mesh</th>
<th>4mm</th>
<th>2mm</th>
<th>1.25mm</th>
<th>1mm</th>
<th>0.75mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max of Mises stress (MPa)</td>
<td>458.7</td>
<td>479.9</td>
<td>456.6</td>
<td>458.8</td>
<td>467.4</td>
</tr>
<tr>
<td>Max of contact stress (MPa)</td>
<td>569.9</td>
<td>697.2</td>
<td>709.1</td>
<td>739.6</td>
<td>754.2</td>
</tr>
<tr>
<td>Area of contact patch (mm²)</td>
<td>214.95</td>
<td>175.281</td>
<td>168.929</td>
<td>163.179</td>
<td>165.673</td>
</tr>
</tbody>
</table>

Figure 4. The FE analysis result of contact area mesh refined to 0.75mm

### B. Dynamic analysis of wheel/rail rolling contact with the explicit calculation

The central difference method in explicit algorithm is relatively easy to achieve parallel computing. Its’ principle is the mature domain decomposition method [5]. The effect of parallel computing mainly is measured by the speedup, which is defined as equation (1) [6]:

$$S_p = \frac{T_1}{T_p}$$

where $T_1$ is computing time of a processor, $T_p$ is computing time of $p$ processors. As there are parallel communication and the imbalances of computing among nodes and the multi-node, the parallel efficiency is a method for further measure of parallel effects, as defined in equation (2):

$$E_p = \frac{S_p}{p} = \frac{T_1}{T_p}$$

In other words, parallel efficiency $E_p$ is defined as the ratio of the speedup $S_p$ and the number of computing nodes, $p$.

As shown in Figure 6, the FE model of wheel/rail rolling contact for dynamic analysis, which of wheel rolls a circuit with initial velocity of 40km/h, is computed for transient analysis by using the network cluster with 12 nodes 96 CPUs. It is noticed that the optimal speedup and parallel efficiency is gotten by the coordination of the number of domain decomposition and the efficiency of CPU according to the size of the FE model, nor by using all nodes and CPUs. The speedup and parallel efficiency of different size of FE model is shown in Table III.

Figure 5. Node-Computing time curve

Figure 6. FE model of wheel/rail rolling contact for Dynamic analysis
<table>
<thead>
<tr>
<th>Number of Node-CPU</th>
<th>Time (s)</th>
<th>Speed-up</th>
<th>Parallel efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>823735</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1-2</td>
<td>447682</td>
<td>1.84</td>
<td>1.84</td>
</tr>
<tr>
<td>1-4</td>
<td>288019</td>
<td>2.86</td>
<td>2.86</td>
</tr>
<tr>
<td>1-8</td>
<td>136380</td>
<td>6.04</td>
<td>6.04</td>
</tr>
<tr>
<td>2-16</td>
<td>207489</td>
<td>3.97</td>
<td>1.98</td>
</tr>
<tr>
<td>3-24</td>
<td>299540</td>
<td>2.75</td>
<td>0.92</td>
</tr>
<tr>
<td>12-96</td>
<td>417120</td>
<td>1.97</td>
<td>0.16</td>
</tr>
</tbody>
</table>

According to the data from table 1, for parallel computing, the more nodes there are, the longer the communicating time is. It has a great impact on parallel speedup and parallel efficiency. Therefore, we should firstly analyze the size of FE model and its memory requirement for computation, and then have a reasonable choice to the number of nodes and CPUs to achieve the best speedup and parallel efficiency. In addition, ABAQUS / Explicit in the analysis process is conditionally stable, which incremental steps must be less than the stability limit, that is, the maximum allowable incremental step. It is decided by the size of the smallest element. So we should avoid too small element in building a FE model, or deal with individual element with mass scaling to enhance the calculation speed.

VI. CONCLUSIONS

(1) Parallel computing of large-scale FE model of wheel/rail rolling contact can be achieved through the domain decomposition to solve the contradictions between calculation accuracy and computing efficiency.

(2) The mode and implementation of network environment of parallel computing is brought forward based on MPI.

(3) For large-scale FE model, alone computer can’t do it, while parallel computer cluster can solve it. The computing time is significantly reduced by a reasonable number of nodes, but not decreased linearly with the number of nodes.

(4) When the size of element of wheel/rail rolling contact zone is refined to 0.75mm, it can be effectively ensure calculation accuracy for engineering analysis.

(5) The center differential method in ABAQUS / Explicit is easy to realize parallel computing. For different size of the FE model, the best speedup and parallel efficiency is achieved by configured the number of nodes and CPUs.

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REFERENCES


