AN INVESTIGATION OF THE OPTIMAL SIMULATION CONDITION FOR NDE WITH THE HELP OF HIGH-SPEED AND HIGH-ACCURACY FEM SIMULATOR

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ABSTRACT
Thanks to recent developments added to our FEM simulator ComWAVE aiming at faster and larger calculation, it can now reproduce realistic situations of actual Nondestructive Evaluation (NDE) in virtual space. In this paper, we demonstrate virtual NDE using the simulator. The model for demonstration is very large 3D body including an inhomogeneous anisotropic weldment part and a crack. We search for the best condition for detecting the crack. Although such a virtual testing usually needs huge computation time to achieve the goal, we show our simulator can do this within practical time by making best use of multi-GPGPUs system and a kind of restart function we have developed.

INTRODUCTION
The role of numerical simulations in Nondestructive Evaluation (NDE) field is very high and will be higher in future because it can teach us the behavior of waves in complex test bodies that are difficult to understand only by experiments. Recently, requests for simulation have a tendency toward larger scale model with high frequency waves to search for small cracks or structures. Not only solving these large problems, practical simulator must equip an ability to solve them as short computation time as possible.

Our original FEM simulator, ComWAVE, has been developing for being practically used mainly in NED [1] [2] and measurement [3]. It can trace every elastic wave modes propagating in elastic bodies by solving the equation of motion faithfully in time domain:

$$\rho \frac{\partial^2 u_i}{\partial t^2} - \frac{\partial \sigma_{ij}}{\partial x_j} - b_i = 0,$$

where $\rho$ is mass density, $u_i$ is displacement vector, $\sigma_{ij}$ is stress tensor, and $b_i$ is external body force vector. The main features of specific techniques adopted in ComWAVE concerning about this paper are summarized as follows:

- Adopting explicit method
- Adopting voxel elements
- Parallelized with MPI

They have enabled us to dealing with very large models which have at the maximum 10 billions of elements within practical running time and memory usage [4].

To be more realistic and practical NDE simulator, ComWAVE is requested to executing iterative calculations such as parameters survey essential for actual testing within practical time. In these backgrounds, we adopted multi-GPGPUs system and have achieved considerable faster calculations [6] [7].

Besides, we have developed new function that is based on the idea of restarting [7]. The essence of the function is to divide a model into plural regions so that the materials whose sound speed is difference belong to different regions. To do this, we can adopt larger time step width in the region which has a material of slower sound speed. This leads to reduction of the total number of steps. On the other hands, we can use larger element size in the region which has a material of higher sound speed. This leads to reduction of running time and memory usage as a result and can deal with equivalently larger models. Moreover, this function solves another annoying issue which is accompanied by large scale models, that is numerical dispersion. In general, numerical dispersion is proportional to the number of steps; a wave
travelling in a large scale model takes many steps to pass through the region and is easy to be influenced by the effect. The function can avoid the trouble because it reduces the number of steps both in higher sound speed region and slower one. In summary, we can expect to dealing with equivalently larger models with keeping accuracy within shorter time using the function.

In this study, we apply our simulator to a typical but complicated large scale 3D model. Making good use of above all techniques and functions, we demonstrate “virtual NDE” throughout the rest of this paper.

MODEL SETUP

The whole aspect of our model is illustrated in Figure 1. It has a crack on the bottom of a test body made of steel. Because the test body has an inhomogeneous anisotropic weldment part, which makes computation time and memory usage increase, in front of the crack, a propagating wave will be deviated from the linear course and this makes it difficult to detect the crack in the best condition. As a probe for sending and receiving, we adopt a matrix array probe made of a kind of acryl illustrated in Figure 2. It has two separated rooms which are for sending and for receiving, respectively. A lot of oscillators are arranged on the roof of each room and they can be driven independently. We drive each oscillator with delay time to focus on the center of the crack given. The central frequency of the injected wave is 2MHz and the shape of the waveform is a kind of wavelet.

Fig. 1 Test model for our virtual NDE

Fig. 2 Composition of matrix array probe
Our final goal here is to search for the best condition to detect the echo coming from the crack by moving the probe along to the x-axis from -4 mm to 10 mm in 1 mm pitch i.e., totally 15 cases. Here 0 mm means the standard position that energies induced at each oscillator and refracted at the boundary between the probe and the test body with 60 degrees angle inclined arrive at the crack simultaneously if there is no weldment.

We analyze the subject in three ways; the first is using parallel computing with MPI (CPUs) as usual and the second is using multi-GPGPUs. Both way solve the full model from sending to receiving. The third way is using the restart function with multi-GPGPUs system. To do this we divide the model into three parts shown in the left of Figure 3. Region 1 and region 3 are composed of the probe and small piece of the test body, and region3 is the test body itself. An injected localized wave crosses over to the next region through the small piece. Note that we only have to run a calculation in region 1 just once because the injected acoustic field into the small peace should be common in all cases. The procedure of the analysis is shown in the right of Figure 3. After calculation in region1 finishes, we give the same acoustic field in each corresponding position in region 2. Of course, we also need to iterate calculations for the same times as the number of cases in region 3. Our multi-GPGPUs system is shown in Figure 4. We connect 5 workstations each of which have two NVIDIA Tesla 2075 by Gigabit Ethernet, i.e., we can be available for 10 GPGPUs at the maximum.

![Fig. 3 Calculation areas for divided model using restart function](image)

![Fig. 4 Multi-GPGPUs system we used](image)
RESULTS

Figure 5 shows snapshots at representative time. The left one is full model calculated by CPUs or multi-GPGPUs (Both of them return identical result) and right one is region 2 of restart model when the probe position is 0 mm. Each snapshot captures a main bulk wave reflected on the crack surface goes back to the probe. Relative echo peaks at each probe position are drawn in Figure 6. The position at which we get the maximum echo is shifted to the positive x direction for +4 mm and we have found the best condition to detect the crack. This occurs because the propagating direction of a wave is bended toward upper direction obeying the crystal axis of the weldment.

![Fig.5 Snapshots of acoustic fields](image1)

![Fig.6 Echo peak obtained by linear scanning](image2)

The main data obtained by the three ways for single case are summarized in Table 1. While the calculation time by 10 paralleled GPGPUs are about 10 times faster than that of 10 paralleled CPUs for full model, restart calculation by 10 GPGPUs achieves about 1.4 times further fast calculation compared with the one by 10 GPGPUs for full model. The reason of the second improvement is explained as follows: In region 1 and 3 of the restart model, we can take time step width about twice as large as that in region 2 because the maximum velocity in region 1 and 3 is about half of the one in region 2. This reduces the number of steps needed propagating through the regions because the number of steps is proportional to the maximum velocity in the model. On the other hands, the element size in region 2 can be twice as large as that in region 1 and 3 because the share wave velocity, that is the minimum velocity, in region 2 is
larger than that in the probe. This also leads to smaller number of steps in region 2 because it is inversely proportional to element size. Furthermore, importantly, the number of elements in region 2 becomes smaller thanks to the larger element size and this contributes to not only shorter computation time but smaller memory usage.

The total time taking to complete the scanning (15 cases) is summarized in Table 2. Note that the total computation time is less than the 15 times the calculation time for single case by 10 GPGPUs. This is because we execute 5 cases of calculation for region 2 simultaneously in parallel. Although GPGPU per one board have limited memory and we need 10 boards to do large scale analysis composed of 10 billions of elements, the detached region 2 can become very small so we need just only 2 GPGPUs.

### Table 1 Main data for single case in three cases

<table>
<thead>
<tr>
<th>CASE</th>
<th>Num. of elements</th>
<th>Element size</th>
<th>Num. of steps</th>
<th>Computation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPUs(Full)</td>
<td>940,710,330</td>
<td>0.055 mm</td>
<td>6477</td>
<td>103.5 hours (10CPUs)</td>
</tr>
<tr>
<td>GPGPUs(Full)</td>
<td>940,710,330</td>
<td>0.055 mm</td>
<td>6477</td>
<td>9.8 hours (10GPUs)</td>
</tr>
<tr>
<td>GPGPUs (Restart)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Region 1</td>
<td>688,187,500</td>
<td>0.04 mm</td>
<td>2,137</td>
<td>1.5 hours (10GPUs)</td>
</tr>
<tr>
<td>Region 2</td>
<td>173,955,600</td>
<td>0.08 mm</td>
<td>3,387</td>
<td>3.9 hours (2GPUs)</td>
</tr>
<tr>
<td>Region 3</td>
<td>688,187,500</td>
<td>0.04 mm</td>
<td>2,137</td>
<td>1.5 hours (10GPUs)</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>-</td>
<td>7,661</td>
<td>6.9 hours</td>
</tr>
</tbody>
</table>

### Table 2 Main data for scanning with multi-GPGPUs system

<table>
<thead>
<tr>
<th>CASE</th>
<th>Num. of iterations</th>
<th>Computation time (15 cases)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region 1</td>
<td>1</td>
<td>1.5 hours (10GPUs)</td>
</tr>
<tr>
<td>Region 2</td>
<td>3 (5 cases run at the same time)</td>
<td>11.7 hours (5 cases x 2GPUs)</td>
</tr>
<tr>
<td>Region 3</td>
<td>15</td>
<td>22.5 hours (10GPUs)</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>35.7 hours</td>
</tr>
</tbody>
</table>

We also diagnose the crack with sector scanning shown in Figure 7. The scan is done with the probe located at the best position and the range of refraction angle for scanning is varied from 50 to 68 degrees for the share wave entering into the test body in 2 degrees pitch. The B-scope figure obtained in the central section is shown in the right of Figure 7. The echo position is slightly different from the crack because a wave is bended in the weldment. It also takes over 1035 hours to get the figure with 10 parallel computing with CPUs system but only s37.8 hours with our multi-GPGPUs system and restart function with divided model.
SUMMARY
In this paper, we assert that practical simulator for NDE must trace every kinds of wave phenomena evoked in large scale 3D virtual test bodies in time domain for searching optimal condition for testing iteratively in standard computation system we can be available easily within practical computation time with considering accuracy. We introduce two techniques to solve this difficulty:

1. Using multi-GPGPUs we try to reduce computation time.
2. Using a kind of restart function, we divide a model into plural parts. This method reduces the scale of each part and enables us to dealing with equivalently larger model. Another advantage of the method is to be considered accuracy.

We apply these methods to a practical 3D model including a complex matrix array probe and a weldment part, and demonstrate virtual NDE searching for the best condition for testing with iterative calculations. We show we can get a solution about 147 hours (15 times of 9.8 hours. See Table 1.) with multi-GPGPUs while it takes about 1552 hours (15 times of 103.5 hours. See Table 1.) to get it with usual CPUs system. Moreover, with making best use of multi-GPGPUs system and the restart function with divided models, we show we can get it about 35.7 hours (See Table 2.).

REFERENCES
4. Ikegami Y, Sakai Y, and Nakamura H, ”A Highly Accurate Ultrasonic Simulator Capable of Over One Billion Elements for Non-Destructive Evaluations”, 7th Int. Conf on NDE in Relation on Structural Integrity for Nuclear and Pressurized Components.

Fig.7 Setup for sector scanning and B-scope figure