ABSTRACT

Ultrasonic guided waves are being widely applied to the long range inspection of piping. The interpretation of the guided wave ultrasonic testing data is challenging because guided waves contain many wave modes with different sound velocities. In order to understand the beam path of each guided wave mode, one of the key issues is to visualize ultrasonic wave propagation. JAPEIC NDE Center has applied the experimental ultrasonic wave visualization technique and the numerical simulation technique of bulk wave propagation to the interpretation of UT data, the analysis of suitable UT condition and the education/training of UT. This paper describes the numerical simulation results of guided wave propagation in pipes by using a large scale three-dimensional FEM code, which can analyze over one billion elements and can use parallel computing system. Procedure of modelling for guided wave generation and the comparison between simulation and experiment are described.

KEYWORDS: Ultrasonic Testing (UT), Guided Wave, Piping, Wave Propagation, FEM, Parallel computing

INTRODUCTION

Ultrasonic guided wave technology is expected to apply to the online inspection, monitoring, and the long range inspection[1-4]. Guided wave has various wave modes with different sound velocity depend on frequency. Therefore, guided wave inspection results are very complicated to interpret the beam path of observed echoes. So, the theoretical analyses, such as modal analyses, mathematical calculation[5], and semi-analytic numerical calculation[6], help us to plan the inspection setup and to interpret the inspection results for simple or basic problems. For practical problems, for example welding, defects, piping support, and flanges, one of the most effective solutions to analyze the guided wave propagation is the calculation by pure FEM.

The purpose of this research is to confirm the applicability of a large scale FEM and a parallel computing technique for simulation of guided wave propagation and prediction of echoes, and to confirm the capability of the FEM code as a simulation tool for complex geometries. This paper presents the guided wave generation model. FEM simulation of guided wave propagation and prediction of echoes are shown. Comparison between simulation results, theoretical results, and experimental results is also discussed.

SIMULATION CODE AND MODELS

A commercial FEM code for large scale three dimensional analysis, which was developed by ITOCHU Techno-Solutions; named COM WAVE[7], was selected to calculate guided wave propagation along tubes and pipes. A parallel computing system which has 60 cores and 124 GByte memories was employed for this computation.

In the present situation of wave generation model, the electrical-mechanical-acoustic problem was not modeled yet. The direction of displacement vector generated by the transmitter was modeled. A schematic diagram of the guided wave generation model in present simulation is shown in Figure 1. This figure shows the cross sections of tubes and probe elements. The blue and red areas are tube and the probe elements respectively. The initial displacement waveform was applied to all surface FEM meshes of tube at each probe element. The directions of displacement vector are indicated by black arrows. Figure 1(a) shows a longitudinal mode (L-mode) excitation model and Figure 1(b) shows a torsional mode (T-mode) excitation model. The receiving model are now under developing. In the present simulation, the receiving information was modeled to detect the displacement waveform of
surface FEM meshes corresponding to the receiver position. The structure of tube model was divided into cubic elements with the maximum size of the elements less than one-fifteenth of the wavelength. Figure 2 shows the straight tubes and pipe model which are used to verify our modeling by comparing the both theoretical and experimental results. Figure 2(a) shows small three tubes model of the same dimensions. The dimensions of each tube are 450mm length, 5mm outer diameter and 1mm thickness. Five cycles of wave which has the center frequency of 1MHz, 500kHz and 200kHz was used for the L-mode excitation in each three tubes. Figure 2(b) shows a pipe model which dimensions are 2,000mm length, 34mm outer diameter and 3.2mm thickness. Five cycles of wave which has the center frequency of 200kHz was used for the L-mode excitation of this pipe. The material parameters used in the calculation is listed in Table 1.

SIMULATION RESULTS

Model A

The simulation results of guided wave propagation in model A is shown in Figure 3. The color bar indicates the amplitude of deformation of the outer surface. In Figure 3, each four result is the snapshots after 2 micro second, 10.2 micro second, 16.6 micro second, and 24 micro second of wave generation respectively. Figure 4 shows the group velocity dispersion curves of Model A in L(0,1) and L(0,2) mode. As pointed out by the white arrow in Figure 3, all waves are axially symmetric modes. Considering the dispersion curves in Figure 4, a wavelet at 200kHz seems to be L(0,1) mode. Two wavelets are shown at 1MHz. Faster and slower wavelet seems to be L(0,2) and L(0,1) mode, respectively. Details of deformation and vibration of each wavelet are shown in Figure 5. The red dotted lines indicate the deformation of outer and inner surface. The green arrows indicate the displacement vector. Figure 5(a) shows a close-up view of the wavelet at 200kHz. This wavelet was axially symmetric and the vibration in the wall direction was asymmetric. Therefore, this wavelet is identified as L(0,1) mode. Figure 5(b) shows a close-up view of the faster wavelet at 1MHz. This wavelet was axially symmetric and the vibration in the wall direction was symmetric. Therefore, this wavelet is identified as L(0,2) mode. Figure 5(c) shows a close-up view of the slower wavelet at 1MHz. This wavelet was axially symmetric and the vibration in the wall direction was asymmetric. Therefore, this wavelet is identified as L(0,1) mode. The wave modes of all wavelets were identified. Good agreement between FEM results and theoretical prediction through dispersion curves was obtained.

Model B

In the case of model B, Figure 6 shows an experimental result of received waveform[8] and a calculated result by FEM. As shown in Figure 6, the time of flight of echoes in the simulated and experimental received waveform was almost equal. Simulated received waveform was similar to the experimental result except for signal amplitude and noise level which had not been modeled in this simulation. Figure 7 shows wave propagation behavior and theoretical dispersion curves of L-Mode. Comparison between FEM simulation and experimental results shows that the FEM simulation corresponds very well to the state of guided wave propagation in actual piping.

TRIAL APPLICATION TO U-BENT MODEL

Figure 8 shows a result of trial FEM simulation on U-bent tube model. The outer diameter and thickness of the tube are 5mm and 1mm. The model structure is shown in Fig. 8(a). Five cycles of wave which has the center frequency of 500kHz was used in the T-mode excitation. The material parameters and simulation conditions used in this simulation is the same as that of Model A. Guided wave propagation through U-bent tube are shown in Figure 8(b) to Figure 8(f). It was recognized that T-mode was mode-converted to a flexural mode (F-mode) at U-bent.
CONCLUSION

As the results of present study, it was found that the large scale FEM simulation is applicable and capable to the simulation of guided wave propagation and "echo" prediction. The research is in progress. As the next stage, we are trying to challenge the simulation of complex geometry model such as the piping which has a welding, an elbow, and defects.

REFERENCES

7) http://www.ctc-g.co.jp/
(a) L-mode excitation  
(b) T-mode excitation

Figure 1 - Cross section of tube and probe elements

(a) Small three tubes model (Model A)  
(b) Pipe model (Model B)

Figure 2 - Schematic diagram of the straight pipe configuration

<table>
<thead>
<tr>
<th>Material (Sound velocity)</th>
<th>Model A</th>
<th>Model B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloy base metal</td>
<td>(V_l=6.0km/sec., V_s=3.04km/sec)</td>
<td>Type 304 stainless steel base metal (V_l=5.7km/sec., V_s=3.1km/sec)</td>
</tr>
<tr>
<td>Dimensions</td>
<td>OD=5mm, t=1mm</td>
<td>OD=34mm, t=3.2mm</td>
</tr>
<tr>
<td>Center frequency</td>
<td>200kHz, 500kHz, 1MHz</td>
<td>200kHz</td>
</tr>
<tr>
<td>Element size</td>
<td>0.1mmx0.1mmx0.1mm</td>
<td>0.2mmx0.2mmx0.2mm</td>
</tr>
<tr>
<td>Total number of the elements</td>
<td>About 100 million</td>
<td>About 3.3 million</td>
</tr>
</tbody>
</table>

Table 1 - Material parameters and simulation conditions
Figure 3 - Simulation results of Model A

Figure 4 - Group velocity dispersion curves for L-Mode (OD=5.0mm, t=1.0mm, Aluminum alloy tube)
Figure 5 - Deformation and vibration display of wavelets
Figure 6 - Comparison of received waveform

Figure 7 - Simulation result of Model B and group velocity dispersion curve
Figure 8 - Guided wave propagation through U-bent tube with T-mode excitation