ABSTRACT

We have developed a new numerical simulation system “ComWAVE” based on finite element method (FEM) which can conduct highly accurate ultrasonic simulations even for models with a huge number of elements over one billion.

In ultrasonic testing (UT) method, the propagation of ultrasonic waves inside the structure is generally too intricate to obtain the conclusion directly from the inspected data, and it is considered to be an interfered sum of several wave phenomena, such as diffraction, surface waves and edge waves, adding to reflection and refraction. This simulator is very useful for a variety of problems associated with UT technologies. The user can observe such an intricate wave phenomena directly, using strong graphic interface, like photo-elasticity testing.

“ComWAVE” can calculate a waveform of A-scan and make an image of B-scan using strong post processing tools. In addition, it has a three-dimensional modeller to make an intricate model easily with CAD data. This powerful tool is very useful for UT engineer to simulate UT, especially welding joints and mechanical parts with intricate geometry.

The authors provide a general explanation of this software “ComWAVE” by showing several results of practical application cases.

INTRODUCTION

Among several NDE methods there is a particularly high demand on ultrasonic testing (UT) because of the simplicity in applying to a wide variety of objects and the potential easiness in evaluation of the associated safety.

In UT methods, the echoes from the internal construction of the object, including some defects, are inspected and analyzed against the ultrasonic excitation from the surface. However, the ultrasonic propagation path in the object is generally too intricate to obtain the conclusion directly from the inspected data, and it is considered to be an interfered sum of several wave phenomena, such as diffraction, surface waves and edge waves, adding to reflection and refraction. In addition, for the intricate shapes of the object, defects tend to occur in areas subjected to stressors, for instance, in the areas of welded part’s boundaries.

Taking into account these factors causing difficulties in the evaluation, research and development works have been continued steadily in several UT technology areas. A remarkable area of recent development is simulation software, which enables to visualize the wave propagation of the intricate field mentioned above by computer analysis [1],[2],[3].

A software package “ComWAVE” using FEM has been developed, which conducts highly accurate ultrasonic simulations for models of over one billion elements [4],[5]. Such a simulator is very useful for a variety of problems associated with UT technologies, because the object structure can be perfectly inspected in both static and operation states by visualizing the wave propagation patterns. The authors provide a general explanation of this software “ComWAVE” by showing several results of practical application cases.
SOFTWARE OUTLINE

ComWAVE calculates the ultrasonic simulation according to Fig. 1. The modelling module consists of two types of modellers which are a basic modeller and an advanced modeller. The basic modeller is used for constructing the simulation model by combining simple shapes such as rectangular, cylinder or tetrahedron etc. The advanced modeller is used for constructing the simulation model by CAD data or function for arbitrary shape definition. The modelling module has the function to combine the basic modeller and advanced modeller. The modelling module has also a probe template function which defines the slant probe and various phased array probes etc. It is defined easily by setting refraction angle, wedge length, array number and incident mode etc.

The pre-processing module is used for defining the send-receive conditions of ultrasonic probe, absorbing boundary conditions, B-scan conditions and phased array probe conditions such as automatic definition of delay time etc.

The computation module can execute parallel jobs on Linux or Windows environments using PC clusters. It includes the automatic mesh generation and running the multi jobs with multi CPU. The top node has a function to combine the result files from each CPU.

For the post-processing module, we have provided many types of visualization such as volume rendering, arbitrary section contour, maximum distribution, particle motions and vector display.
### Modeling:
- Probe templates
  (Angled probe, Phased array, etc.)
- Basic modeler
  (Combination of Boxes, Cylinders and Tetrahedrons, etc.)
- Advanced modeler
  (CAD data Import, Modeling of intricate objects)

### Pre-processing:
- Data setting of ultrasonic send/receive conditions.
- Data setting of absorbing boundaries.
- Automatically setting of delay time for phased array.
- Data setting of B-scan condition
  - etc.

### Computation:
- Solver can be parallelized by MPI.
- OS: Windows Vista / XP, Linux
- Over one billion elements available.
- Batch job function provided

### Post-processing:
- Visualization of Ultrasonic propagation (volume rendering, contour map at any cross section, maximum distribution, particle motions, vector display, etc.)
- Display of waveforms at any point.
- Display of A-scan and B-scan.
  - etc.

### Examples of probe model
- Slant probes
- Phased arrays
- Matrix array

### Examples of inspection model
- Flow meter
- Concrete
- Turbine disk
- Weldment

### Examples of simulation output
- Contour plot
- Volume rendering
- Maximum amplitude distribution
- A-scan
- B-scan
- Vector plot
- Particle motions

**Figure 1 - Software outline of ComWAVE©**
**METHOD**

In the simulations of ultrasonic propagation, the Finite Difference Method (FDM) is more commonly employed than FEM, although FEM has a number of inherent advantages over FDM. For example, FEM can satisfy the free-surface condition of nature, as the governing equation of FEM is derived based on the traction-free condition at the outer boundary of the medium. FEM has also advantages in the definition of anisotropic material like weldment and of the frequency dependent attenuation. However, FDM has proven to be popular because it usually requires less computer memory and less computation time than FEM.

To overcome these drawbacks of FEM, we used a grid consisting of voxels (rectangular prisms) and derived an explicit formula. ‘Voxel’ is a term used in the field of computer graphics to indicate a volume pixel, which in geometry is the shape of a rectangular prism. The use of voxel mesh leads to a significant reduction in the memory requirements and computation times. Generation of the voxel mesh is as easy as that in FDM as shown in Fig. 2, and FEM with voxel mesh has an advantage in terms of ease of describing the shape of the model.

Table 1 shows required memory and relative CPU time of each simulation methods. Therefore, Our Voxel FEM code can be used with a significant reduction in the memory requirements and computation times, as same as FDM.

<table>
<thead>
<tr>
<th></th>
<th>Required memory</th>
<th>Relative CPU Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDM</td>
<td>20MB/Mdof</td>
<td>1</td>
</tr>
<tr>
<td>FEM</td>
<td>400MB/Mdof *</td>
<td>5</td>
</tr>
<tr>
<td>Voxel FEM</td>
<td>20MB/Mdof</td>
<td>1.4</td>
</tr>
</tbody>
</table>

*estimated from Bao et al.[6].  
dof=degree of freedom

Table 1 - Required memory and relative CPU time of each simulation methods
Figure 3 - Relation of parallel numbers to computing time that is derived by calculations for two billion elements and 5,000 time steps.

(CPU: Pentium Xeon 3.0GHz (64bit), Required memory: 120GB)

Fig. 3 shows the relation of parallel numbers to computing time that is derived by calculations for two billion elements and 5,000 time steps. Our voxel FEM code can be parallelized by MPI on Linux or Windows platforms. It can solve the problem of two billion elements within under 40 hours using 32 parallel calculations.

Fig. 4 shows another advantage of FEM that is the definition of anisotropic material calculated by our voxel FEM code. It shows a significant anisotropy of ultrasonic propagation in weldment of austenitic stainless steel. FEM rotate the crystal axis easily by D-matrix rotation according to Euler angle.

$$D'_{IJ} = [M(\theta, \phi, \psi)]D[M(\theta, \phi, \psi)]$$

($\theta, \phi, \psi$ : Euler angle, [D] : D-matrix)

Figure 4 - Comparing the propagation characteristic of isotropic and anisotropic medium.
Intrinsic attenuation (parameterized by Qp and Qs) is one of the key factors governing wave propagation over long distances such as simulation for the guide wave. We therefore introduced Rayleigh damping into our FEM code so that we can fit the Q value at two different frequency points to suit a broader frequency range [7]. As shown in Fig. 5, the Rayleigh damping model fitted to the Qs value at 1MHz and 4MHz and the Qp value at 2MHz. Consequently, the usefulness of the Rayleigh damping model is confirmed in terms of enabling a broader frequency range for the Q dumping model. ComWAVE can include this Rayleigh damping model with using simple parameters.

Figure 5 - Comparing the Rayleigh dumping with Q dumping

(a) S-wave attenuation
(Gray line: Rayleigh dumping, Black line: Q dumping(Qs=5,000))

(b) P-wave attenuation
(Gray line: Rayleigh dumping, Black line: Q dumping(Qp=10,000))

Figure 5 - Comparing the Rayleigh dumping with Q dumping
EFFECTIVENESS OF OUR SIMULATOR

In UT methods, the echo from the internal construction of the object, having some defects inside, are inspected and analyzed against the ultrasonic excitation from the surface.

In that case, the accuracy of recognizing the ultrasonic propagation path is important to analyze the echo from the defects. However, the ultrasonic propagation path in the object is generally too intricate, and it is considered to be an interfered sum of several wave phenomena, such as diffraction, surface waves and edge waves, adding to reflection and refraction. In addition, for the intricate shapes of the object, defects tend to occur in areas subjected to stressors, for instance, in the areas of weldment.

For example, Fig. 6 shows the simulation results of propagation in austenite stainless steel weldment having different crystal axes. It shows that, though the weldment shapes are same, the ultrasonic propagation path is greatly affected by material structure of anisotropy in the weldment.

![Figure 6 - Comparing the propagation path in austenite stainless steel weldment having different crystal axis.](image)

(a) Crystal axis in weldment : ±10°  
(b) Crystal axis in weldment : ±45°

Figure 6 - Comparing the propagation path in austenite stainless steel weldment having different crystal axis.

![Figure 7 - Comparing the propagation path in cylinder stick using photo-elasticity testing and simulation.](image)

(a) Photo-elasticity testing [8]  
(b) Simulation results

Figure 7 - Comparing the propagation path in cylinder stick using photo-elasticity testing and simulation.
Fig. 7 shows the visualization of ultrasonic propagation paths in a cylinder stick using photo-elasticity testing by Eguchi et al. [8] and our simulation. The propagation paths in the stick are good agreements with photo-elasticity testing results. However both results show the refraction angle of a P-wave more shallow than of an S-wave. In general, the refraction angle of the P-wave delivered by Snell’s law on the plane refraction surface makes a steeper angle than that of the S-wave. That is inverse relation which is shown by Fig. 6. This inverse relation has been explained by Eguchi et al. as the difference between the shapes of refraction surface; one is cylinder, another is plane. Unlike a plane surface, the refraction surface of a cylinder makes differences in transfer coefficient at each incident points of wave front. Consequently, it shows that the visualization of simulation is very useful for preventing misunderstanding of the propagation paths in intricate structures.

SOME APPLICATIONS

In this section, we show three applications using our software. The first is a flaw in the austenitic stainless steel weldment simulation, in which the result of detected waveform is compared with an experiment. The second is B-scan simulation with a new function. The final is the guide-wave simulation applied to pipe inspection.

A flaw in the austenitic stainless steel weldment simulation

The two-dimensional large-scale FEM code was used for calculation of natural flaw in austenitic steel weldment. The analysis model is shown in Fig. 8 which refers to modelling of Komura et al. [2)]. This model is the same as the actual inspection specimen of 28mm thickness SUS304 steel plate with the weldment. A flaw whose height is approximately 5mm was observed at the centre of the weldment. The flaw’s shape was defined by observation results as shown in Fig. 8(c). The crystal axis was defined by a modified Ogilvy’s model. When the parameters related to the weld shape were input, the anisotropic structure at any position within the weldment was determined by mathematical expressions in Ogilvy’s model [9]. The inspection condition was 2MHz, and 45-degree longitudinal wave.

The longitudinal wave propagation contours of this model are shown in Fig. 9(a). It is obvious that the ultrasonic wave propagation and scattering are affected by the structure of the austenitic weldment. The A-scan waveform of this austenitic stainless model is shown in Fig. 9(b). A-scope waveform of simulation result is shown in Fig. 9(c).

Consequently, the waveform, arrival time and wave amplitude of simulation correspond with the experimental result. Thus, it is recognized that this simulator is effective to analyze the ultrasonic inspection testing of austenitic stainless steel.
28mm

Longitudinal wave (2MHz, 45deg)

(a) Analysis model

(b) Crystal axis distributions that is defined by Ogilvy model. [9]

(c) Modeled flaw

Figure 8 - Analysis model of a flaw in austenitic stainless steel and modelled flaw surface

(a) Longitudinal wave contour at 9µs

(b) Experimental result for A-scope

(c) Simulation result for A-scope

Figure 9 - Longitudinal wave contour and A-scope waveforms of a flaw in austenitic stainless steel weldment.
B-scan simulation with phased-array probe to inspect the train rail

Using B-scan function that is a newly introduced function of ComWAVE Ver. 3.0, we have simulated B-scan display with phased-array probe to inspect the train rail that includes three types of defects: parallel defects of 3mm and 5mm length and angled defects of 5mm length and 30°.

The analysis model is shown in Fig. 10 that refers to modelling of Kushida et. al.,[10]. The inspection conditions were 64ch immersion phased array on the rail, 2MHz, water distance 20mm, and driving 32ch to inspect with linear-scan and sector-scan as shown in Fig. 10. The aim of this simulation is to clarify the difference of B-scan display results between linear-scan and sector-scan calculations.

The B-scan display results are shown in Fig. 11(a). The B-scan display of liner-scan shows that the echo from angled defects becomes weaker than that of the parallel defects. On the other hand, B-scan display of sector-scan shows that the echo from angled defects becomes stronger than linear-scan results. The meaning of these different results is explained by the result of wave propagation paths shown in Fig. 11(b). The propagation path of the linear-scan from angled defects is not in alignment with the incident path, unlike the propagation path of the sector-scan.

Consequently, it is recognized that this simulator is effective to evaluate the B-scan display by comparing not only B-scan display but also propagation paths which would not be seen easily through an experiment.

Figure 10 - Simulation models of B-scan calculation to inspect the train rail.
Figure 11 - Ultrasonic propagation paths and B-scan results for B-scan simulation
Guide wave simulation

A guide-wave propagates long distance through concentrating the wave energy to the specimen surface or material boundaries. The inspection with guide-wave has been paid attention to recently, to inspect broad areas for pipe or plate within strict inspection area.

However, guide-waves include many waves such as surface waves, plate waves, lamb and love waves. They are dispersed according to propagation. This characteristic makes the guide-wave inspection hard to apply to actual inspection.

We introduce the simulation of guide-wave inspection for round direction of pipe shown in Fig. 12 that refers to modelling of Nishino et. al.,[11]. This simulation model is constructed with a huge-scale three dimensional model that has 950 million elements.

The visualization results of guide wave propagation in the pipe with 3D model simulation are shown in Fig. 13. These results show the volume rendering, displacement vector at central section of round direction and vertical displacement waveform on the outer pipe.

Consequently, it is recognized that this simulator is effective when observing the guide-wave dispersion characteristic using not only waveform but also visualization of guide-wave propagation in the pipe which can not be seen easily by experiment. We will study the optimal conditions such as different incident angle or frequency conditions etc., to make less dispersing conditions of a guide-wave.

Figure 12 - Simulation models of guide wave simulation.
Figure 13 - Ultrasonic propagation snapshot with volume rendering, displacement A-scan and displacement vector on the centre section of propagation path.
CONCLUSIONS

In UT method, the ultrasonic propagation path in the object is generally too much intricate to obtain the conclusion directly from the inspected data, and it is considered to be an interfered sum of several wave phenomena, such as diffraction, surface waves and edge waves, adding to reflection and refraction. In addition, for the intricate shapes of the object, defects tend to occur in areas subjected to stressors, for instance, in the areas of welded part’s boundaries.

To solve these problems, we adopt voxel FEM to our software that makes better use of memory requirement, computation time and easy definition for free-surface condition, anisotropy and attenuation, than conventional methods such as FEM and FDM. In addition, our software ComWAVE has flexible modelling and visualization functions and is easy to use without technical knowledge and simulation skills.

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