Simulation of Ultrasonic Fields and Echo Signals using Cross-Section Photograph of Test Object and FDTD Method

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Abstract

We present a simulation technique of ultrasonic fields and echo signals, that uses a digitized cross-section photograph of a test object and a digitized cross-section figure of an ultrasonic probe as input data. The input data file is referred to as a shape file. In the shape file, different colors are assigned to different materials, for example, red for a piezoelectric transducer, green for the wedge of a probe, and blue for a test object, for the purpose of distinguishing between the different materials. Each color contains information on material parameters, such as the velocity of a longitudinal wave in the material, that of a shear wave, and the material density. Using the shape file, ultrasonic transmitted fields, scattered fields, and echo signals are calculated by a two-dimensional elastic finite-difference time domain (FDTD) method. The pixel size of the shape file is set to be the same as the grid size used in the FDTD simulation. A simulation result using real photographs of butt weld joints is presented.

Keywords: Simulation, FDTD method, Ultrasonic fields, Echo signal, Shape file

1. Introduction

Recently the maintenance of aging structures such as steel bridges and plants has become an important subject. Nondestructive ultrasonic testing is expected to help maintain such structures effectively.

A suitable testing method depends on the type of structure. If a method is investigated by experiments alone, the time required to realize the method becomes long, and the cost becomes high. Investigation by simulation is very effective for reducing both the time and the cost.

Several simulation models for calculating ultrasonic fields in solids have been reported, for example, the finite difference method (FDM), finite element method (FEM), boundary element method (BEM), and finite-difference time domain (FDTD) method. We are interested in the FDTD method because of the simplicity of the scheme. However, it is intricate work to input the data concerning a test object when its shape is very complicated, such as butt weld joints, even when the FDTD method is used.

In this paper, we demonstrate a simulation technique using a cross-section photograph of the test object as input data to decrease the amount of intricate work when using the two-dimensional elastic FDTD method.

2. FDTD method

If a test object is an isotropic medium, the particle velocities and the stresses in two dimensions are given by Eqs. (1) - (5),

$$\frac{\partial v_x}{\partial t} = \frac{1}{\rho}\left(\frac{\partial T_{xx}}{\partial x} + \frac{\partial T_{xz}}{\partial z}\right) \tag{1}$$

$$\frac{\partial v_z}{\partial t} = \frac{1}{\rho}\left(\frac{\partial T_{xz}}{\partial x} + \frac{\partial T_{zz}}{\partial z}\right) \tag{2}$$

$$\frac{\partial T_{xx}}{\partial t} = \rho\left\{V_l^2\frac{\partial v_x}{\partial x} + \left(V_l^2 - 2V_s^2\right)\frac{\partial v_z}{\partial z}\right\} \tag{3}$$

$$\frac{\partial T_{zz}}{\partial t} = \rho\left\{\left(V_l^2 - 2V_s^2\right)\frac{\partial v_x}{\partial x} + V_l^2\frac{\partial v_z}{\partial z}\right\} \tag{4}$$

$$\frac{\partial T_{xz}}{\partial t} = \rho V_s^2\left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right), \tag{5}$$

where v_x and v_z are the particle velocities; T_{xx}, T_{zz}, and T_{xz} are the stresses; V_l and V_s are the velocities of a longitudinal wave and shear wave in the test object, respectively, and ρ is the density of the test object. In the FDTD method[1], particle velocities and stresses are calculated like a leap-frog in the time domain using Eqs. (1) - (5) at staggered grids.

3. Shape file

It is intricate work to input data into a computer when the shape of the test object is very complicated. To decrease the amount of work, a digitized cross-section photograph of the test object and a digitized cross-section figure of an ultrasonic probe are used. An example of a cross-section photograph[2] is shown in Fig. 1. The photograph shows butt weld joints including a flaw. The thickness of the steel plate is 17 mm.
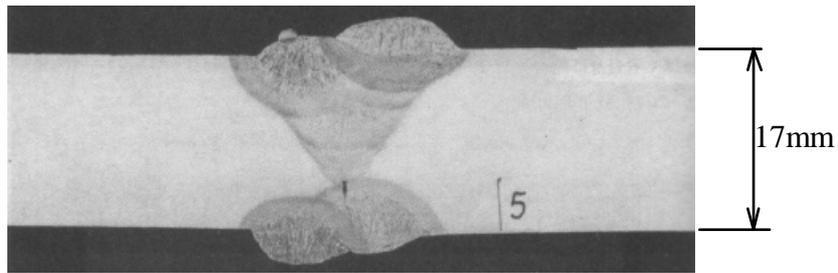
Figure 1. An example of a digitized cross-section photograph of a test object.

An angle beam technique is usually employed in the testing of butt weld joints. An example of a digitized cross-section figure of an ultrasonic angle probe is shown in Fig. 2. The angle of incidence is 52.4° , and the size of the transducer is 10 mm.
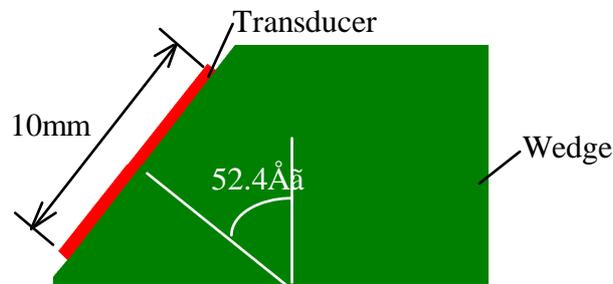

Figure 2. An example of a digitized cross-section figure of an ultrasonic angle probe.

By combining the photograph shown in Fig. 1 and the figure shown in Fig. 2, the input data is obtained. The shape file is shown in Fig. 3. The angle probe is set on the test object for angle beam testing. In the shape file, different colors are assigned to different materials, red for a piezoelectric transducer, green for the wedge of a probe, and blue for a test object, for the purpose of distinguishing the different materials. The pixel size of the shape file is equal to the grid size used in the FDTD method.
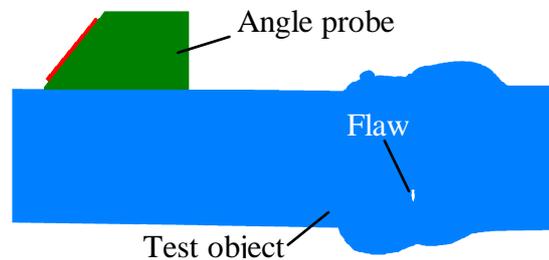

Figure 3. A shape file combining the photograph shown in Fig. 1 and the figure shown in Fig. 2.

4. Material parameters

As shown in Fig. 3, the transducer, the wedge, and the test object are distinguished by their colors

in the shape file. The colors represent the material parameters; the velocities of a longitudinal wave and shear wave in the material, and the material density in Eqs. (1) - (5). A table including these parameters is prepared before beginning the simulation, and these parameters are read from the table for each pixel. An example of a parameter table is shown in Table 1. At red pixels (in the transducer), the corresponding grids are employed as transmitting and receiving points. Thus, the material parameters corresponding to red are not shown in Table 1.

The flaw represented by the white color in the shape file is considered as a cavity. In this area, stresses are set to zero to satisfy the boundary conditions.

Table 1. Parameter table.

Color	V_l [m/s]	V_s [m/s]	ρ [kg/m^3]
Red	-	-	-
Green	2730	1430	1170
Blue	5930	3240	7700

5. Simulation results

Ultrasonic fields obtained by the FDTD method using the shape file and the parameter table are shown in Fig. 4. In the simulation, the grid size is 20 µm, and the time step is 1.7 ns. These fields show the amplitude of particle velocities. The shear vertical (SV) wave is generated by mode conversion at the interface and propagates in the test object in the direction of 70°, which agrees with the angle of refraction expected by Snell's law. The scattered fields by the flaw are also shown in the figure. The echo signal is obtained by continuing the calculation until the scattered fields propagate to the transducer. The received echo signal obtained by the simulation is shown in Fig. 5.
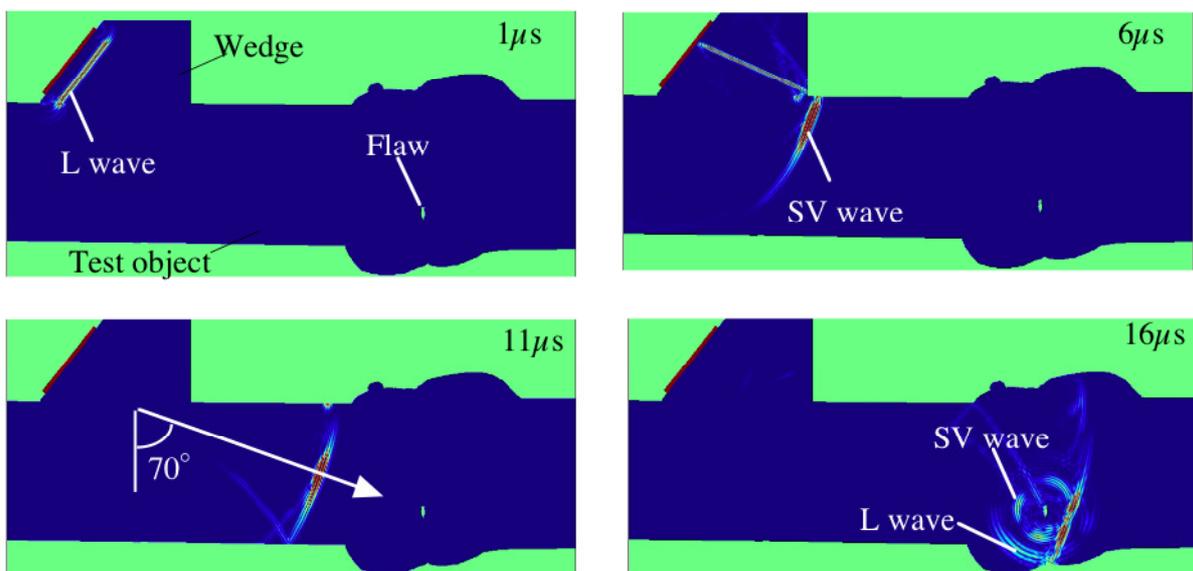

Figure 4. Ultrasonic fields obtained by the simulation using the shape file and the parameter table.
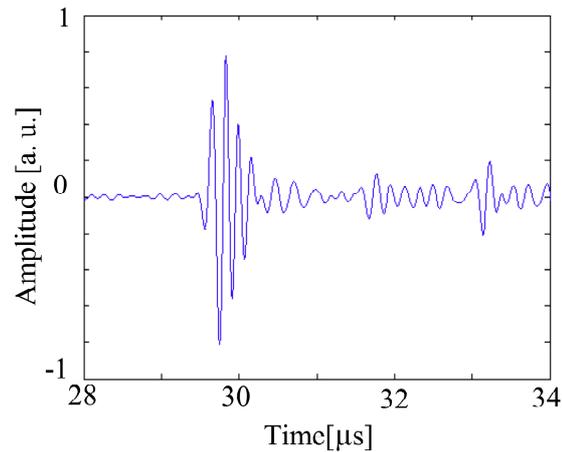
Figure 5. The received echo signal obtained by the simulation.

6. Validity of the simulation technique

The validity of the simulation technique is verified by experiments using a side-drilled hole and an angle probe whose parameters are known. The shape file including the angle probe and the side-drilled hole is shown in Fig. 6. The angle of incidence is $36.6°$ (the angle of refraction is $45°$) and the size of the transducer is 6 mm. The characteristics of the angle probe are shown in Fig. 7. The time response shown in Fig. 7 is measured in another experiment using an ultrasonic test instrument, as discussed in reference[3], and the frequency characteristic is obtained by a fast Fourier transform (FFT). The diameter of the side-drilled hole is 2 mm.

The simulation using the shape file and the experiment using the angle probe and the side-drilled hole are performed. The echo signals obtained by the simulation and experiment are shown in Fig. 8. As shown in the figure, the experimental result is in good agreement with the simulated result.
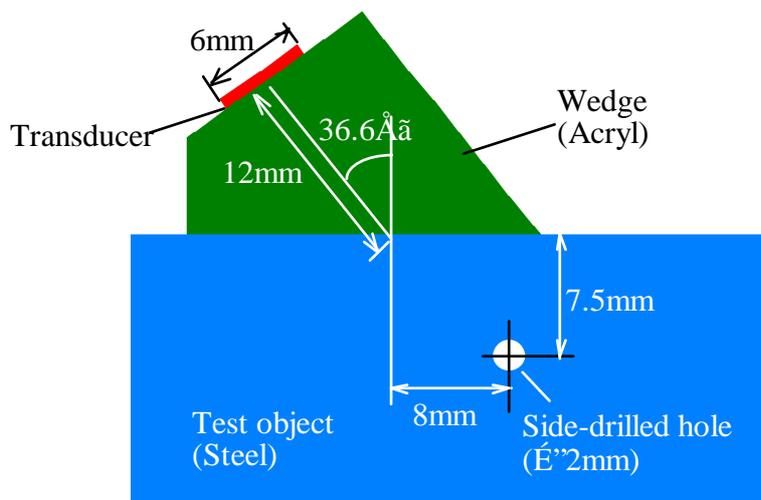

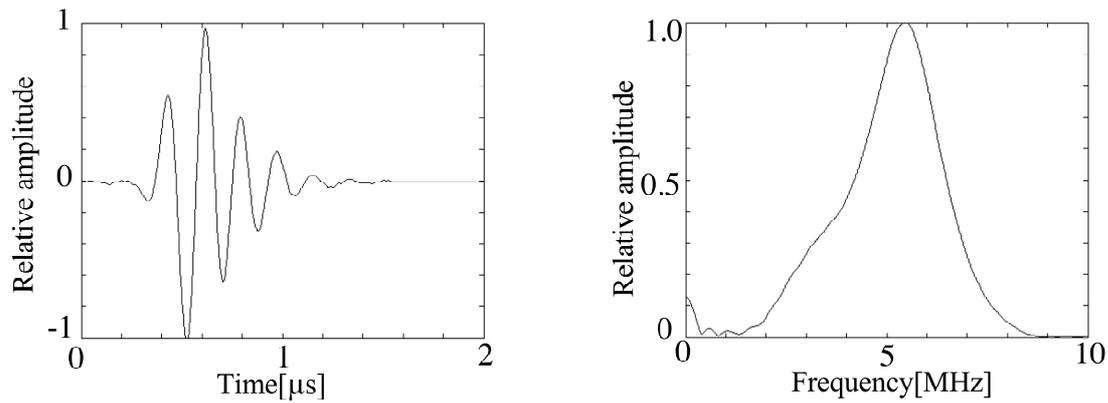Figure 6. The shape file including the angle probe and the side-drilled hole.
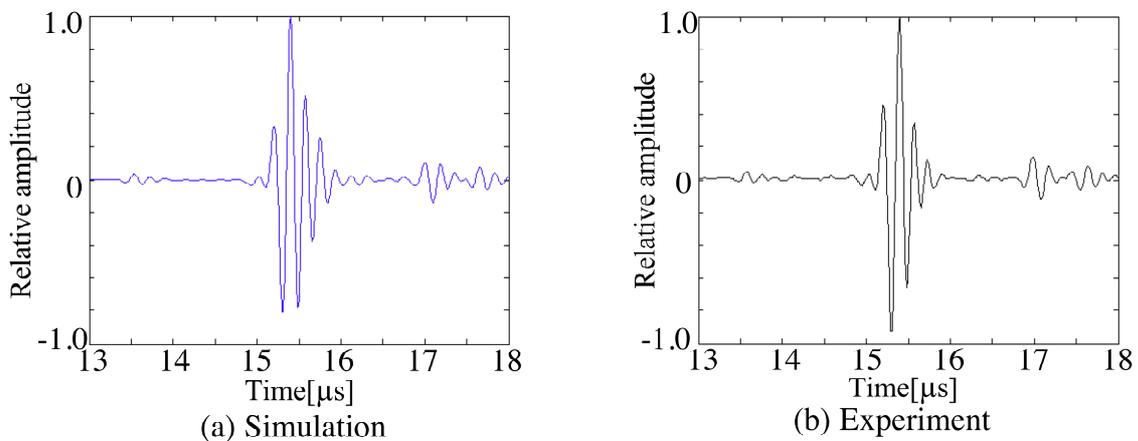
Figure 7. The characteristics of the angle probe.

(a) Simulation   (b) Experiment

Figure 8. The echo signals obtained by the simulation and the experiment.

7. Conclusions

A simulation technique that uses a shape file as input data is shown. The shape file is obtained by combining a cross-section photograph of a test object and a cross-section figure of an ultrasonic probe. It is easy to prepare the shape file even when the shapes of a flaw and the test object are complicated. Using the shape file, ultrasonic transmitted fields, scattered fields, and echo signals are calculated by the two-dimensional elastic FDTD method. The validity of the simulation technique is verified by experiments using a side-drilled hole as a flaw.

References

[1] J. Virieux, "P-SV wave propagation in heterogeneous media: Velocity-stress finite difference method," Geophysics, 1986, Vol. 51, pp.889-901.

[2] Japanese Society for Non-destructive Inspection edit., "Hihakaikensa Gairon", 1993, p 36 [in Japanese].

[3] S. Wadaka, N. Nagatsuka, K. Misu, T. Kimura, M. Koike and H. Ichikawa, "A pulse compression ultrasonic test instrument and its applications," *Rev. Progr. QNDE*, 1996, Vol. 15, pp.1779-1786.