Numerical Simulation of Ultrasonic Wave Propagation in Flawed Domain

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Abstract

Ultrasonic inspection is one of the key tools of nondestructive testing in which understanding nature of wave propagation in a flawed domain is important. By FEM, it is possible to simulate responses in a domain due to ultrasonic excitation through solution of assembled equations. In the present work simulations for (i) normal beam incidence wave propagation problem in a composite domain, (ii) angular wave propagation in a single domain are done. For a composite domain with acoustically dissimilar materials, wave propagation is associated with reflection and transmission. In the composite domain case with normal beam incidence, the reflection and transmission coefficients are computed and found to be in good agreement with the theoretical results based on energy principle. A special case study is undertaken for a rectangular domain with a circular hole. Responses at different points on the travel path reveal a different wave speed to exist at the circular boundary.

1. Introduction

Ultrasonic inspection is one of the key tools of nondestructive testing. Nature of ultrasonic wave propagation is understood by inspecting responses at different locations in the domain. This, however, is expensive in conventional experimental procedure. In contrast such observations could be made by simulating propagation of acoustic waves in target domains. Finite Element Method is a numerical tool using which such simulations can be done effectively. Features of wave propagating in a domain depend on various properties like density, modulus of elasticity, Poisson’s ratio and loading. As FEM divides the domain into numerous small elements and forms element equation for each of them, modeling of composite domains with multi-properties can be adeptly handled [1,2]. Responses at different locations due to prescribed excitation are simultaneously available through solution of the assembled equations. Out of many existing professional software, ANSYS has versatile capabilities in applying FE methodology in different fields. In the present case simulations for a normal beam incidence wave propagation problem in a composite domain, angular wave propagation in single domain are done in ANSYS environment. Composite domains, made of acoustically dissimilar materials, exhibit reflection and transmission phenomena and respective coefficients are computed to be found in good agreement with the theoretical results based on energy principle. The longitudinal and Rayleigh mode are clearly observed and their velocities are checked against the corresponding theoretical values. A special case study is undertaken for a rectangular domain with a circular hole. Responses at different points on the travel path reveal a different wave speed to exist at the circular boundary.

2. Simulating Wave propagation in ANSYS

ANSYS is a general-purpose FEA software package by which field problems of various engineering disciplines can be tackled in a systematic manner. ANSYS has a comprehensive Graphical User Interface (GUI) that gives users easy, interactive access to program functions, commands, documentation, and reference material. An intuitive menu system helps users to navigate through the ANSYS program for pre-processing, processing and post-processing. It is, however, the pre-processing step that consumes the maximum time of the user. The present task of simulating acoustic wave propagation phenomena in a domain is implemented in ANSYS 10.0 using its transient solution utilities. The element type, mesh size, material properties, time step and other time integration parameters are appropriately input [3]. Full domain analysis is conducted and full domain response is collected at each time step to extract various propagation characteristics.

Simulating Normal Beam Incidence on a Composite Domain

The simulation of a normally incident acoustic wave on a composite domain made of Aluminium and Lead is schematically shown in Fig. 1. F is the exciting force of sinusoidal nature with 1MHz central frequency while A, B, C and D are the response points. The domain is discretized by 4 node quadrilateral elements having 2 degrees of freedom at each node. Being a transient problem, the spatial and temporal discretization is done in such a way that the minimum wave length of the wave in the domain contains 8-10 nodes. The time step should be such that the maximum wave speed in the medium is not able to cross one spatial size in one time
The highest and slowest speeds occur in the longitudinal (L) and Rayleigh mode (R) respectively, and may be computed as $C_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$ and $C_R = 0.5c_L$, $c_R = 0.9c_s$. Again, $C_R = \lambda_R \times f$ where $f$ = frequency and $\lambda_R$ = wavelength of Raleigh wave (5). Considering there should be at least 8-10 nodes/minimum wave length, side edge lengths are taken as $\Delta x = \Delta y = \Delta R/8$ and time step, $\Delta T < (\Delta x/C_L)$.

Table 1 : Properties of the materials of the composite domain

<table>
<thead>
<tr>
<th>Properties</th>
<th>Aluminium</th>
<th>Lead</th>
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<tbody>
<tr>
<td>Modulus of elasticity (E)</td>
<td>70 GPa</td>
<td>16 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio ((\nu))</td>
<td>0.25</td>
<td>0.44</td>
</tr>
<tr>
<td>Density ((\rho))</td>
<td>2.63 (kg/m(^3))</td>
<td>11.35 (kg/m(^3))</td>
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</tbody>
</table>

A sinusoidal load with a frequency of 1MHz is applied for 1 microsecond at midpoint of bottom boundary of the domain. Total analysis time is 10 microsecond. The Y-DOF of the upper boundary is zero and the midpoint of the upper edge is fixed. A-scan plots just before and after point B are shown in Figs. 2(a) and 2(b) respectively.

The full domain response for the above case at 1.8e-06 second is shown in Fig. 3. The MATLAB plot, generated from full domain result, clearly shows the propagation.

Responses shown in Figs. 2(a) and 2(b) correspond to node just before B at (10, 2.4) and the node just after B at (10, 2.6) respectively. The calculated times of travel are 0.4e-6 and 0.5e-6 sec. The times of responses obtained from graphs nearly match those values. Now, from the energy considerations, transmissivity (T) and reflectivity (R) are obtained as $T = \frac{4Z_1Z_2}{Z_1+Z_2}$, $R = \frac{(Z_1-Z_2)^2}{(Z_1+Z_2)^2}$, where $Z = \rho c$, the acoustic impedance. From the properties given in Table 1, T and R for the Al/Pb interface are computed as 0.937 and 0.0628 respectively. Also from the plots, the amplitude ratio which is a measure of transmissivity is calculated as 0.949.

### 3. Simulating Angle Beam Incidence on a Single Domain

The simulation case of a rectangular domain of 30mm by 21mm made of Al subjected to an angular excitation at the bottom left corner is shown in Fig. 4. The figure also shows different points along the travel path at which responses are collected. The excitation is sinusoidal with a frequency of 1 MHz and is inclined at 45°.
The red line, blue line and the green line in the above plots represent the X-displacement, the Y-displacement and the resultant displacement respectively. The coordinates of the point B is (7.2, 7.2) and thus AB is 10.18mm. The calculated time which the wave should take to cover this distance is 1.73e-06 sec. The first response time in Fig. 5(a) is also seen at approximately 1.67e-06 sec to show the correctness of the simulation. The travel of the wave to point F can take place in two points. Considering circular wave fronts, it may reach F directly from A, or it may reach F via AD and DF after one reflection. The calculated time for the first case is 5.72e-06 second which is close to the value of 5.75e-06 sec obtained from the graph. The calculated time along the path ADF is 7.5e-06 sec. Existence of circular wave front is also evident from the full domain response at 5.1e-06 sec as shown in Fig. 6.

From Fig. 6 it is also clear that a shear wave front propagates behind the longitudinal wave front. Existence of the slowest Rayleigh wave at the side edges of the domain is also clearly visible.

4. Simulating Angle Beam Incidence on a Rectangular Domain with Hole

In Fig. 7, a rectangular domain of 30mm by 21mm made of Al with a circular hole at the centre is shown. It subjected to an angular excitation at the bottom left corner while the top edge is treated fixed. The excitation, sinusoidal in nature, is done for 1e-06 second and the responses are taken at several locations along a diagonal line. Full domain responses at specific times are also taken to study the nature of wave propagation in presence of the discontinuity.

Response at point D for the entire time of simulation is shown in Fig. 8. To reach to the point D (22.5, 15.6) the wave is expected to follow the tangent path ATPD as shown in Fig. 7. The distance of PD is 7.524 mm. If the wave covers the distances AT and PD with the velocity $C_l$ and the distance TP with the velocity $0.809C_l$ then it will reach the point D at 5.33e-06 sec. Also the time of 1st response, obtained from the graph shown in Fig. 8, is 5.36e-06 sec which is quite satisfactory. This confirms for the wave to travel in a different mode along the discontinuity boundary.
Conclusions

Results in the preceding section reveal utility of Finite Element Method in simulating acoustic waves in single, composite and flawed domain. The reflection, transmission phenomena at the interface of dissimilar materials are clearly visible in the simulation process. In presence of flaws or discontinuities with free boundary, waves are found to travel with a different velocity according to the nature of the converted mode.

References