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<th>Finite-Element Solution of Horizontally Polarized Shear Wave Scattering in an Elastic Plate</th>
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Finite-Element Solution of Horizontally Polarized Shear Wave Scattering in an Elastic Plate

MASANORI KOSHIBA, SENIOR MEMBER, IEEE, KOJI HASEGAWA, AND MICHI SUZUKI, SENIOR MEMBER, IEEE

Abstract—A method of the solution of scattering of horizontally polarized shear waves in an elastic plate is described. The approach is a combination of the finite-element method and the analytical method. In this approach, both the propagating and evanescent higher order modes are taken into account, and the restriction in the previous work that the number of assumed waveguides modes be equal to the number of boundary finite-element nodal points is removed. This approach is applicable to the frequency range in which the plate waveguide propagates multimodes. Numerical examples on the scattering by a step discontinuity, a wedge-shaped crack, and a metal strip are given.

I. INTRODUCTION

SCATTERING of guided waves by discontinuities in an elastic plate is a basic problem in nondestructive evaluation and also has important implications with regard to electrical signal-processing functions, and the scattering of horizontally polarized shear (SH) waves has been investigated extensively [1]-[5]. Recently, the numerical methods based on the finite-element method (FEM) have been developed for the analysis of the scattering of SH waves by arbitrarily shaped discontinuities in an elastic plate. Sabbagh et al. [6] have analyzed the scattering of SH waves by a step discontinuity joining two plates using a combined method of the FEM and circuit theory. In their approach it is assumed that the plate waveguide propagates a single mode only, and all the higher order modes in the waveguide are neglected. Abduljabbar et al. [7] have analyzed the scattering of SH waves by an infinitely thin crack normal to the surface of a plate using a combined method of the FEM and analytical technique. In their approach the higher-order modes are taken into account, but the stresses along the boundary separating the interior finite-element region from the exterior region are discretized by utilizing a stress function expansion (analogous to the number of normal modes are independent of each other and the nodal points can be arbitrarily spaced along the interface boundary. This approach is applicable to the frequency range in which the plate waveguide propagates multimodes. To show the validity and usefulness of this formulation, computed results are given for a step discontinuity, a wedge-shaped crack, and a metal strip. Accuracy of the solution is investigated in detail.

II. BASIC EQUATIONS

We consider the plate waveguide junction as shown in Fig. 1, where the boundaries $\Gamma_1$ and $\Gamma_2$ connect the discontinuity region to the plate waveguide 1 and 2, respectively, the boundaries $\Gamma_3$ and $\Gamma_4$ are the stress-free surface, and the region $\Omega$ with the boundaries $\Gamma_1$ to $\Gamma_4$ completely encloses the discontinuities.

Assuming that there is no variation in the $z$-direction, we have the following basic equations for SH waves [1]:

$$\partial T_{xx}/\partial x + \partial T_{xy}/\partial y - j\omega \rho v_z = 0 \quad (1)$$

and

$$j\omega T_{xx} = \mu \partial v_z/\partial x \quad (2a)$$

$$j\omega T_{xy} = \mu \partial v_z/\partial y \quad (2b)$$

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where \( v_z \) is the z component of the particle velocity, \( T_{xz} \) and \( T_{zy} \) are the stresses, \( \omega \) is the angular frequency, \( \rho \) is the mass density, and \( \mu \) is the Lamé constant.

### III. Mathematical Formulation

#### A. Finite-Element Approach

Dividing the region \( \Omega \) into a number of second-order triangular elements with six nodal points as shown in Fig. 1, the particle velocity \( v_z \) within each element may be written as

\[
v_z = \{N\}^T \{v_z\}_e \tag{3}
\]

where \( \{v_z\}_e \) is the particle velocity vector corresponding to the nodal points within each element, \( \{N\} \) is the shape function vector [7], [8], [10]–[14], and \( T \cdot \) and \( \cdot \) denote a transpose, a column vector, and a row vector, respectively. The advantage of an arbitrary triangular shape in approximating to any boundary shape has been demonstrated in [10]. Also, the usefulness of the second-order triangular element has been discussed in [12] and [13].

Using a Galerkin procedure on (1) and integrating by parts, we obtain

\[
\int_{\gamma} [\partial \{N\}/\partial x] T_{zx} + [\partial \{N\}/\partial y] T_{zy} + j\omega \rho \{N\} v_z \, dx \, dy - \int_{\Gamma} \{N\} T_{zn} \, d\Gamma = \{0\} \tag{4}
\]

where the first and second integrations on the left side are carried over the element subdomain \( \Omega_e \), and the contour \( \Gamma_e \) of \( \Omega_e \), respectively, \( \{0\} \) is a null vector, and

\[
T_{zn} = T_{xz}n_x + T_{zy}n_y. \tag{5}
\]

Here \( n_x \) and \( n_y \) are the x and y components of an outward normal unit vector to \( \Gamma_e \), respectively.

Noting that \( T_{zn} \) is continuous across \( \Gamma_e \) and \( T_{zn} = 0 \) on \( \Gamma_3 \) and \( \Gamma_4 \), from (2) to (4) the following global matrix equation is derived

\[
[A]\{v_z\} = \sum_{i=1}^{2} \sum_{e} j\omega \int_{\Omega_e} \{N\} T_{xz,i}(x^{(i)} = 0, y^{(i)}) \, dy^{(i)} \tag{6}
\]

where

\[
[A] = \sum_e \int_{\Omega_e} \left[ \mu_e (\partial \{N\}/\partial x) (\partial \{N\}/\partial x) \right. \\
+ \mu_e (\partial \{N\}/\partial y) (\partial \{N\}/\partial y) \left. \right. \\
- \omega^2 \rho \{N\} \{N\}^T \right] \, dx \, dy. \tag{7}
\]

Here \( \{v_z\}_e \) is the nodal particle velocity vector, \( \Sigma_e \) and \( \Sigma'_e \) extend over all different elements and the elements related to \( \Gamma_i \) (\( i = 1, 2 \)), respectively, \( T_{xz,i}(x^{(i)} = 0, y^{(i)}) \) is the stress on \( \Gamma_i \), and \( \{N\}_i \) is the shape function vector on \( \Gamma_i \), namely \( \{N\}_i = \{N(x^{(i)} = 0, y^{(i)})\} \).

Using the shape function vector \( \{N\}_e \), the particle velocity \( v_{z,i} \) and the stress \( T_{xz,i} \) on \( \Gamma_i \) may be discretized as follows:

\[
v_{z,i}(x^{(i)} = 0, y^{(i)}) = \{N\}_i^T \{v_z\}_i, \tag{8}
\]

\[
T_{xz,i}(x^{(i)} = 0, y^{(i)}) = \{N\}_i^T \{T_{xz}\}_i. \tag{9}
\]

where \( \{v_z\}_i, \) and \( \{T_{xz}\}_i \) are the particle velocity vector and the stress vector corresponding to the nodal points within each element related to \( \Gamma_i \), respectively.

Substituting (8) and (9) into (6), we obtain

\[
[A]\{v_z\}_B = \begin{bmatrix} \{0\} \\ \{B\} \end{bmatrix} \tag{10}
\]

where

\[
{v_z}_B = \begin{bmatrix} \{v_z\}_1 \\ \{v_z\}_2 \end{bmatrix} \tag{11}
\]

\[
{T_{xz}}_B = \begin{bmatrix} \{T_{xz}\}_1 \\ \{T_{xz}\}_2 \end{bmatrix} \tag{12}
\]

\[
[B] = \begin{bmatrix} [B]_1 & [0] \\ [0] & [B]_2 \end{bmatrix} \tag{13}
\]

and

\[
[B]_i = j\omega \sum_e \int_{\Omega_e} \{N\}_i \{N\}_i^T \, dy^{(i)}, \quad i = 1, 2. \tag{14}
\]

Here the components of the \( \{v_z\}_i \) vector are the values of \( v_z \) at the nodal points in \( \Omega \) except \( \Gamma_1 \) and \( \Gamma_2 \), the components of the \( \{v_z\}_i \) and \( \{T_{xz}\}_i \) vectors are the values of \( v_z \) and \( T_{xz} \) at the nodal points on \( \Gamma_i \), respectively, and \( [0] \) is a zero matrix.

#### B. Analytical Approach

The internal fields in the waveguide \( i = 1, 2 \) in Fig. 1 are represented by the sum of the normal modes as [1], [2], [15]

\[
v_{z,i}(x^{(i)}, y^{(i)}) = \sum_n \left[ a_{in} \exp(-j\beta_{in}x^{(i)}) \\
+ b_{in} \exp(j\beta_{in}x^{(i)}) \right] f_{in}(y^{(i)}) \tag{15a}
\]

where

\[
[A] = \sum_e \int_{\Omega_e} \left[ \mu_e (\partial \{N\}/\partial x) (\partial \{N\}/\partial x) \right. \\
+ \mu_e (\partial \{N\}/\partial y) (\partial \{N\}/\partial y) \left. \right. \\
- \omega^2 \rho \{N\} \{N\}^T \right] \, dx \, dy. \tag{7}
\]
\[-T_{xx,i}(x^{(i)}, y^{(i)}) = \sum_n Y_n \{a_n \exp(-j\beta_{in} x^{(i)}) - b_n \exp(j\beta_{in} x^{(i)})\} g_n(y^{(i)}) \tag{15b}\]

where

\[
\beta_{in} = \sqrt{k_n^2 - (n\pi/d_i)^2}
\]

\[
Y_{in} = \mu_i \beta_{in}/\omega
\]

\[
f_{in}(y^{(i)}) = g_{in}(y^{(0)}) = \sqrt{1_n/d_i} \cos(n\pi y^{(i)}/d_i)
\]

\[
k_{si} = \omega \sqrt{\rho_i/\mu_i}
\]

and

\[
l_i = \begin{cases} 1, & n = 0 \\ 2, & n \neq 0 \end{cases}
\tag{20}\]

Here \(a_n\) and \(b_n\) are the amplitudes of the \(n\)th mode \((n = 0, 1, 2, \cdots)\) in the waveguide \(i\) propagating (or decaying) toward the \(+x^{(i)}\) and \(-x^{(i)}\) directions, respectively.

Now, assuming that the \(m\)th mode \((m = 0, 1, 2, \cdots)\) of unit amplitude is incident from the left of waveguide 1 in Fig. 1, the amplitudes of normal modes may be written as

\[
b_{ln} = \begin{cases} 1, & n = m \\ 0, & n \neq m \end{cases}
\tag{21a}\]

\[
b_{2n} = 0.
\tag{21b}\]

Considering (15) and (20), \(v_{z,i}\) and \(T_{xx,i}\) on \(\Gamma_i\) may be expressed as

\[
v_{z,i}(x^{(i)} = 0, y^{(i)}) = \delta_{ii} \cdot 2f_{im}(y^{(i)})
\]

\[
+ \int_0^{d_i} \sum_n \{1/Y_{in}\} f_{in}(y^{(i)}) f_{in}(y_0^{(i)}) \cdot [-T_{xx,i}(x^{(i)} = 0, y_0^{(i)})] dy_0^{(i)}
\]

\[
-T_{xx,i}(x^{(i)} = 0, y^{(i)}) = -\delta_{ii} \cdot 2Y_{1m}g_{1m}(y^{(1)})
\]

\[
+ \int_0^{d_i} \sum_n Y_{in}g_{in}(y^{(i)}) g_{in}(y_0^{(i)}) \cdot v_{z,i}(x^{(i)} = 0, y_0^{(i)}) dy_0^{(i)}
\tag{22}\]

where \(\delta_{ii}\) is the Kronecker \(\delta\).

Using (8) and (9), (22) and (23) can be discretized as follows:

\[
\{v_z\}_i = \delta_{ii} \{f\}_1 - [F]_i \{T_{xx}\}_i
\tag{24}\]

\[
-T_{xx,i} = \delta_{ii} \{g\}_1 + [G]_i \{v_z\}_i
\tag{25}\]

where

\[
\{f\}_1 = 2\{f_m\}_1
\tag{26}\]

\[
\{g\}_1 = -2Y_{1m}\{g_m\}_1
\tag{27}\]

\[
[F]_i = \sum_n (1/Y_{in}) \{f_n\}_i \int_0^{d_i} f_{in}(y_0^{(i)}) \\
\cdot \{N(x^{(i)} = 0, y_0^{(i)})\} dy_0^{(i)}
\tag{28}\]

\[
[G]_i = \sum_n Y_{in} \{g_n\}_i \int_0^{d_i} g_{in}(y_0^{(i)}) \\
\cdot \{N(x^{(i)} = 0, y_0^{(i)})\} dy_0^{(i)}
\tag{29}\]

Here the components of the \(\{f_m\}_i\) and \(\{g_n\}_i\) vectors are the values of \(f_{in}(y^{(i)})\) and \(g_{in}(y^{(i)})\) at the nodal points on \(\Gamma_i\), respectively.

C. Combination of Finite-Element and Analytical Relations

Using (11) and (12), from (10) and (24) we obtain the following final matrix equation:

\[
\begin{bmatrix}
[A] & [0] \\
[0] & [B]
\end{bmatrix}
\begin{bmatrix}
\{v_z\}_i \\
\{v_z\}_B
\end{bmatrix}
= \begin{bmatrix}
\{0\} \\
\{0\}
\end{bmatrix}
\tag{30}\]

Similarly, from (10) and (25) we obtain the following final matrix equation:

\[
\begin{bmatrix}
[A] & [0] \\
[0] & [-G]
\end{bmatrix}
\begin{bmatrix}
\{v_z\}_i \\
\{v_z\}_B
\end{bmatrix}
= \begin{bmatrix}
\{g\}_1 \\
\{g\}
\end{bmatrix}
\tag{31}\]

where

\[
\{f\}_1 = \begin{cases} \{f\}_1 \\ \{0\} \end{cases}
\tag{32}\]

\[
\{g\}_1 = \begin{cases} \{g\}_1 \\ \{0\} \end{cases}
\tag{33}\]

\[
[F] = \begin{bmatrix} [F]_1 & [0] \end{bmatrix}
\tag{34}\]

\[
[G] = \begin{bmatrix} [G]_1 & [0] \\
[0] & [G]_2
\end{bmatrix}
\tag{35}\]

Here \([1]\) is a unit matrix.

The values of \(v_z\) at the nodal points on \(\Gamma_i\) \((i = 1, 2)\), namely \(\{v_z\}_i\) are computed from (30) or (31), and then by using (8), \(v_{z,i}\) on \(\Gamma_i\) is calculated from these values.

The solutions \(v_{z,i}\) allow the determination of the reflection coefficient \(R_{mn}\) and the transmission coefficient \(T_{mn}\) of the \(n\)th propagating mode for the \(m\)th incident mode as fol-
Reflection coefficient $R_{00}$ of the zeroth mode at the step, and (29), more nodal points on analysis using (31) is larger than that in the analysis using can be reduced by increasing the number of elements. The condition of power conservation may be written as 

$$\sum_{n=0}^{n_1-1} |R_{mn}|^2 + \sum_{n=0}^{n_2-1} |T_{mn}|^2 = P_{total} = 1$$  \hspace{1cm} (38)$$

where $n_i$ is the number of the propagating modes in the waveguide $i$.

IV. COMPUTED RESULTS

First, we consider the symmetric step joining two plates and subdivided one half of the discontinuity region into second-order triangular elements as shown in Fig. 2, where the zeroth mode is incident from the left of the plate with thickness $d_1$, $d_1/d_2 = 1.7$, $96$ ($N_E$) elements are used, and the number of the nodal points ($N_p$) is 233. Table I shows the numbers $n_1$ and $n_2$ of the propagating modes in the plates with thicknesses $d_1$ and $d_2$, respectively. Table II shows the real and imaginary parts of the reflection coefficient $R_{00}$ of the zeroth mode at the step, where the computed results are obtained by using (30). Table III shows the energy error $(1 - P_{total})$, where the computed results are obtained by using (30) and (31). $N_{IM}$ ($i = 1, 2$) is the number of the normal modes in the waveguide $i$ used in (28) and (29). Here we set $N_{IM} = N_{2M} = N_{M}$. In these tables, the results of $N_E = 384$ ($N_p = 849$) and of $N_E = 846$ ($N_p = 1849$) are also presented. From Table II it is found that for smaller values of $k_2d_2$, both values of real and imaginary parts converge with $N_E = 96$ (see the values for $k_2d_2 = 1.0$, 5.0, and 10.0), but for larger values of $k_2d_2$, the values of imaginary part do not converge with $N_E = 96$ (see the values for $k_2d_2 = 20.0$ and 30.0). The convergence is obtained in the case of $N_E = 384$. From Table III it is found that the energy error can be reduced by increasing the number of elements. The larger the value of $N_E$, becomes, the larger the energy error also becomes. This is due to the fact that when discretizing the normal modes with larger values of $n$ in (28) and (29), more nodal points on $\Gamma_i$ ($i = 1, 2$) in Fig. 2 are necessary. In practice, it is sufficient to consider the propagating modes and a few evanescent higher order modes in (28) and (29). The difference between the values calculated from (30) and the values calculated from (31) is relatively small, but, generally, the energy error in the analysis using (31) is larger than that in the analysis using (30). Therefore, we present below only the results obtained by using (30). It is generally difficult to determine a priori the discretization fineness required to achieve sufficient accuracy. The finite-element method with a suitable mesh refinement strategy [11], [14] may be useful for accurate analysis.

Next, we consider a surface crack in a plate. Results for an infinitely thin crack are given in graphical form by Abduljabbar et al. [7]. Our results agreed perfectly with the results in [7] to the accuracy that can be discerned on the graphs.

Fig. 3(a)–(c) show the magnitude of the reflection coefficient $R_{mn}$ of a wedge-shaped crack as a function of the wedge apex angle $\tan \theta$ for the zeroth ($m = 0$), first ($m = 1$), and second ($m = 2$) incident modes, respectively, where $k_2d_2 = 13.5$ and the reflection coefficient of the mode of order less than $m$ can be computed from the relation $R_{mn} = R_{m0}$ [7]. The number of the nodal points along the interface boundary corresponding to the boundary $\Gamma_i$ ($i = 1, 2$) in Fig. 1 is 41, and 10 normal modes in the waveguide $i$ are considered in (28). The reflection coefficient is considerably influenced by the wedge apex angle. At an appropriate value of $\theta$, the conversion coefficient for the fourth reflected mode becomes larger than the conversion coefficients for the other reflected modes.

Lastly, we consider a metal strip on one surface of a fused quartz plate and assume that the zeroth mode is incident [16]. Fig. 4 shows the magnitude of the reflection coefficient $R_{00}$ of a metal strip as a function of the normalized strip thickness $h/\lambda$, where $\lambda$ is the wavelength of the incident wave, $\lambda = 2\pi/k_2$, $d/\lambda = 0.25$, and the normalized strip width $a/\lambda = 0.25$. The reflectivity of this SH wave is considerably large compared with the Rayleigh-wave reflection from a metal strip on a semi-infinite substrate [17].
TABLE II  
REAL AND IMAGINARY PARTS OF REFLECTION COEFFICIENT $R_{00}$ OF ZEROTH MODE

<table>
<thead>
<tr>
<th>$N_E$</th>
<th>$k_d$</th>
<th>$N_M = 15$</th>
<th>Real Part</th>
<th>$N_M = 30$</th>
<th>Imaginary Part</th>
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</tr>
<tr>
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<td>0.261</td>
<td>0.261</td>
<td>0.261</td>
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</tr>
<tr>
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<td>0.400</td>
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</tr>
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<td>0.414</td>
<td>0.414</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
</tr>
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<td>1.0</td>
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<td>0.261</td>
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<td>0.040</td>
<td>0.040</td>
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<tr>
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<tr>
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<tr>
<td>30.0</td>
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<td>0.414</td>
<td>0.010</td>
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TABLE III  
ENERGY ERROR IN THE ANALYSIS OF STEP DISCONTINUITY IN FIG. 2

<table>
<thead>
<tr>
<th>$N_E$</th>
<th>$k_d$</th>
<th>$N_M = 15$</th>
<th>Equation (30)</th>
<th>$N_M = 30$</th>
<th>Equation (31)</th>
<th>$N_M = 50$</th>
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<td>6.0 $\times 10^{-7}$</td>
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<td>-3.4 $\times 10^{-4}$</td>
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</tr>
<tr>
<td>5.0</td>
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<td>1.0 $\times 10^{-7}$</td>
<td>-4.3 $\times 10^{-9}$</td>
<td>-2.3 $\times 10^{-6}$</td>
<td>-3.0 $\times 10^{-4}$</td>
<td>-1.1 $\times 10^{-3}$</td>
</tr>
<tr>
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<td>7.0 $\times 10^{-5}$</td>
<td>9.8 $\times 10^{-7}$</td>
<td>-1.8 $\times 10^{-6}$</td>
<td>9.8 $\times 10^{-5}$</td>
<td>-5.8 $\times 10^{-2}$</td>
</tr>
<tr>
<td>20.0</td>
<td>1.6 $\times 10^{-5}$</td>
<td>5.1 $\times 10^{-4}$</td>
<td>3.0 $\times 10^{-4}$</td>
<td>4.2 $\times 10^{-5}$</td>
<td>3.0 $\times 10^{-4}$</td>
<td>-1.1 $\times 10^{-3}$</td>
</tr>
<tr>
<td>30.0</td>
<td>6.9 $\times 10^{-5}$</td>
<td>2.2 $\times 10^{-3}$</td>
<td>2.2 $\times 10^{-3}$</td>
<td>-4.3 $\times 10^{-5}$</td>
<td>-8.8 $\times 10^{-5}$</td>
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Fig. 3. Reflection coefficient of wedge-shaped crack for (a) zeroth, (b) first, and (c) second incident modes.
Fig. 4. Reflection coefficient of metal strip for zeroth incident mode.

V. CONCLUSION

A method of analysis, based on the finite-element approach and the analytical approach, was developed for the solution of scattering of SH waves in an elastic plate. This method is useful for inhomogeneous discontinuities of arbitrary shape. Numerical examples are presented for a step discontinuity, a wedge-shaped crack, and a metal strip.

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REFERENCES


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