Simulating the Sound Propagation of Guided Waves Using the Elastodynamic Finite Integration Technique (EFIT)

M.-U. RAHMAN and J. PRAGER

ABSTRACT

The successful design of Structural Health Monitoring Systems requires efficient simulation tools. Especially for implementing ultrasonic monitoring methods the insight into sound propagation problems inside the structure is essential when using guided waves. Although the sound propagation of guided waves in plate like structures and pipes is well understood, for more complex geometries or anisotropic materials simulations are necessary to predict the received signal depending on the type of excitation.

In this contribution an innovative approach is presented for the simulation of propagation of guided waves using Elastodynamic Finite Integration Technique (EFIT). Starting with simple plate like geometries the dispersive behavior is illustrated by analyzing the propagation of different modes. Furthermore, selective excitation is introduced into the model and mode-flaw interactions are studied on different flaw types. The investigation is extended by modeling the wave propagation in structures with more complex geometries. The validity of the simulation results is verified by comparing with experimental data.

INTRODUCTION

Guided waves travel in plates and hollow cylinders over large distances and therefore, are suitable for integrity tests and health monitoring of large scale structures. However, the non-destructive testing (NDT) using guided waves suffers from major drawbacks because of the dispersive nature of the wave propagation and the increasing number of propagating modes at higher frequencies [1]. To overcome such difficulties the phased array transducers can be used to facilitate a selective excitation of individual modes with a single mechanical setup [2]. To analyse the excitation mechanism a numerical simulation of the wave propagation inside the transducer and the excited plate is employed.

Mehbub-Ur Rahman, Jens Prager, Department 8.4, Federal Institute for Materials Research and Testing, Unter den Eichen 87, 12205 Berlin

Due to the complex nature of wave propagation and difficulties in the excitation of different modes, it is imperative to use modern simulation tools. The Elastodynamic Finite Integration Technique (EFIT) is a well-accepted quantitative modeling tool in non-destructive testing using ultrasound. To model the elastodynamic problem using EFIT we discretize the governing equations in integral form on a staggered voxel grid in space [3]. For the time discretization an explicit leap-frog scheme is chosen [4].

In this paper, we model the excitation using a phased array transducer and the propagation of guided waves in plate like structures in 2-D using EFIT. Two sets of simulation results are presented. In the first step, the sound propagation in the wedge of a phased array transducer is simulated. The generated guided waves (Lamb waves) in the plate are simulated in the second step. Finally, the simulation results are validated against the measurement results and thus, the feasibility of using EFIT to model the generation and propagation of Lamb waves in plate like structures is verified.

GENERATION OF LAMB WAVES USING A PHASED ARRAY TRANSDUCER

As discussed before, Lamb waves can be generated using a conventional phased array transducer. Such a transducer offers selective excitation of single modes by defining a trace wavelength λ_{trace} without changing the mechanical set-up (see Fig. 1a). The wedge angle φ_w can be incorporated to the swivel angle α according to

$$\alpha = \sin^{-1}\left(\frac{c_w}{c_{ph}}\right) - \varphi_w \quad , \tag{1}$$

where c_w represents the velocity of the longitudinal wave in wedge and c_{ph} is given by $c_{ph} = f \cdot \lambda_{trace}$. By controlling the delay time of each element of the phased array transducer electronically we choose the angle of impingement β and thus, a normal force pattern with a trace wavelength λ_{trace} at the surface of the structure [5]. For a thin plate with the thickness d=2 mm and the center frequency of the excitation pulse f=1.5 MHz, we obtain $f \cdot d$=3 MHz·mm. Using Eq. 1 and the dispersion curve (see Fig. 1b) we compute the following results for the required angles:

TABLE 1. Modal behavior for a 2 mm steel plate and a transducer with a centre frequency of f=1.5 MHz.

Mode	**λ_{trace} (in mm)**	**c_{ph} (in m/s)**	**c_{gr} (in m/s)**	**β (in °)**
A_0	1,9	2865	3160	72
S_0	2,3	3423	2123	53

SIMULATION RESULTS

According to Table 1 we can excite S_0 mode at the impingement angle β=53°. This analytical value will be used to validate the simulation results using EFIT.

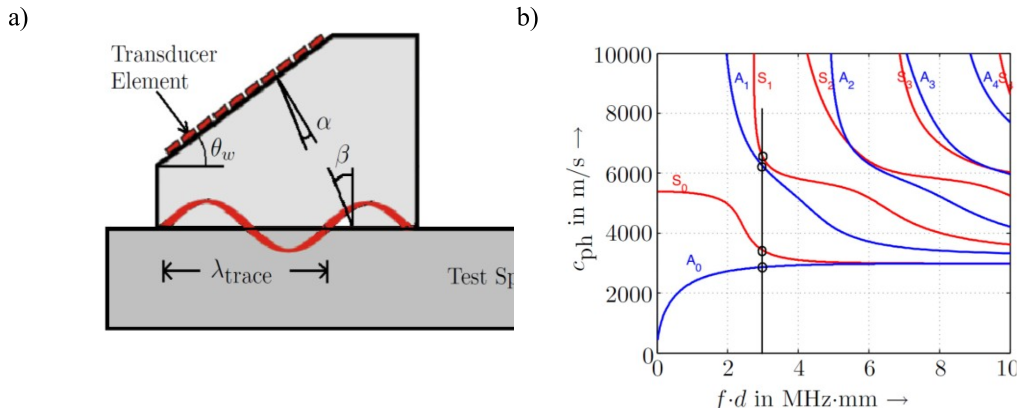

Figure 1. a) Experimental setup using a phased array transducer and b) dispersion diagram for a steel plate with thickness d=2 mm.

The sound field in the wedge is simulated using the EFIT-tool and the simulation results are shown in Fig. 2 which represents the sound field at $T=11.36$ μs.

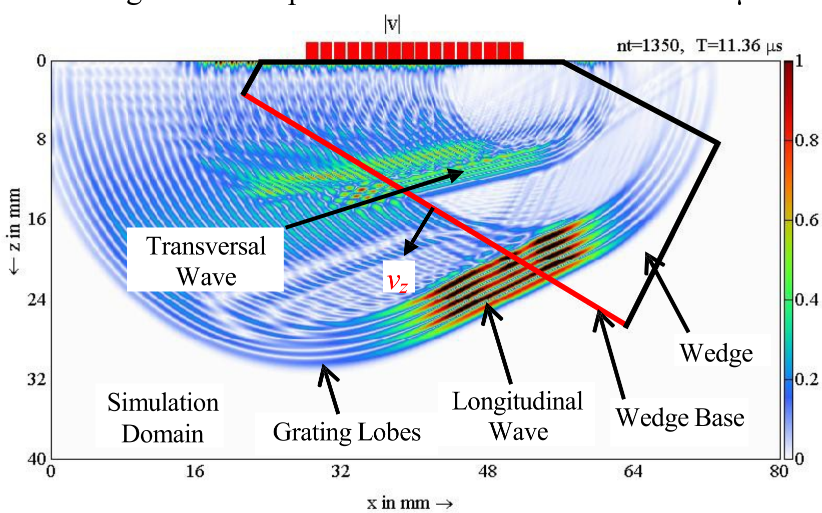

Figure 2. Sound field in wedge using angle of impingement β*=53°.*

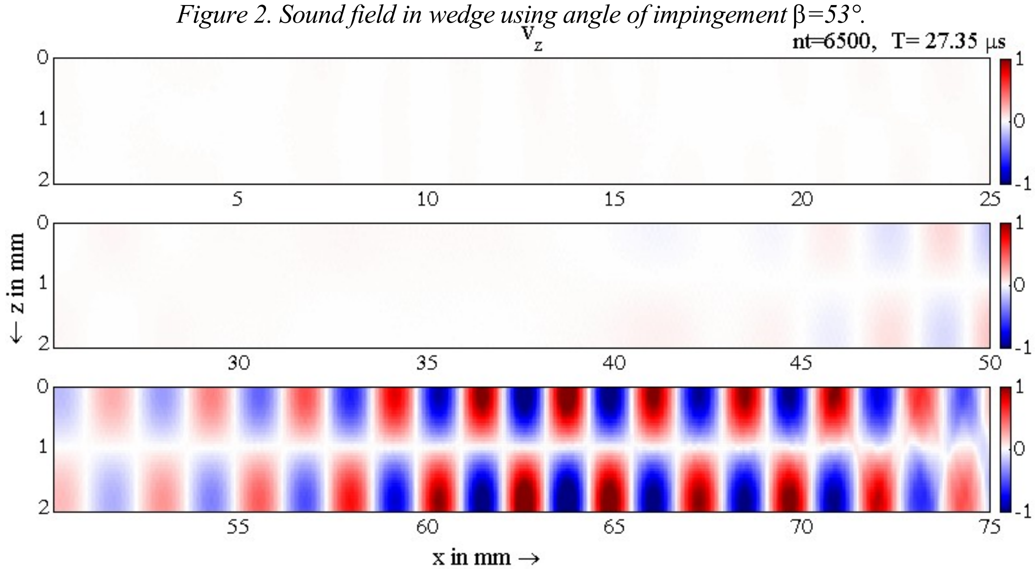

Figure 3. Lamb wave propagation of the S_0 mode in a 2 mm steel plate (first 75 mm is shown here) at a frequency f=1.5 MHz with a phased array transducer using angle of impingement β=53°.

Here we assume the wedge is located in a homogeneous region filled with the same material as the wedge. This facilitates exact computation of the signal at the wedge base in the time-domain. Reflections inside the wedge, however, are neglected. The small red boxes at the top represent the elements of the phased array transducer, whereas the geometry of the wedge is shown with thick black lines. The normal component of the particle velocity is computed along the base of the wedge and is denoted as v_z in Fig. 2. This component acts as the excitation pulse to generate Lamb waves in the plate in the subsequent simulation. Using this excitation pulse the ultrasonic wave field in a steel plate with a thickness d=2 mm is modeled in Fig. 3 which shows the v_z component in the steel plate at time T=*27*.35 µs to demonstrate the Lamb waves.

Here, we divide the steel plate into small plate segments of 25 mm length each for the ease of visualization. The first three segments are shown in Fig. 3 where we observe mostly S_0 mode which agrees with the analytical results presented in Table 1.

MEASUREMENT RESULTS AND VALIDATION

The measurements are performed for the angle of impingement β = 52° for S_0 mode. However, this value slightly differs from the theoretical value presented in Table 1. As the strongest excitation is observed during the measurements at this slightly altered angle of impingement, the measurements and comparisons are performed at this value.

For the experimental analysis of the wave field at the wedge base and on the plate the fields are scanned using a laser vibrometer. A grid of 13×355 scan points is set at the wedge base. To evaluate the excited Lamb mode spectra, a grid of 7×7271 scan points is placed on the plate in front of the transducer. A 2-D Fourier transform of the obtained data, in space along the propagation direction and in time domain, yields the measured excitation spectra at the wedge base and in the plate. These spectra are qualitatively compared to the simulated normal component of the particle velocity v_z (k,f).

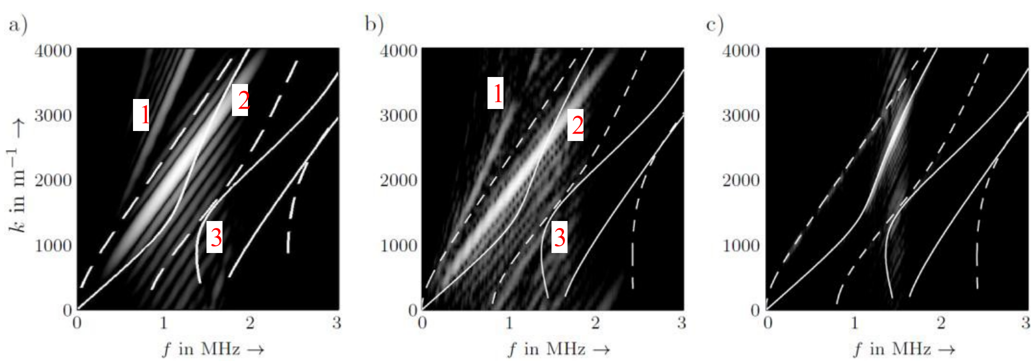

Figure 4. Excitation of S_0 mode for angle of Impingement β = 52°: a) simulated and b) measured spectra at the wedge base; c) excited modes in the plate. Scaling from -30 dB (deepest black) to 0 dB (brightest white). Marked: theoretical dispersion curves for the first three symmetric (-) and anti-symmetric (--) modes.

Fig. 4 shows the results for the excitation of S_0 mode for the angle of impingement β = 52°. The simulated and the measured spectra at the wedge base are presented in Fig. 4a and Fig. 4b, respectively. The theoretical dispersion curves are overlaid with solid and dashed lines, where the symmetric modes are represented with solid lines and the anti-symmetric modes are denoted by dashed lines. Apart from slight differences in frequency distribution, the agreements between the simulated and the measured wedge base signals are good.

The extent of the excitation in the frequency f as well as in the wave number k-domain is clearly visible here. The excitation is by far not limited to the central frequency of the transducer and the theoretical wave number, instead there is a strong extension in both domains. This extension is however, due to the bandwidth of the excitation pulse which results a finite extension of the excitation in the time and space domain. The major parts (marked as 2 in Fig. 4) of the measured signals are, however, located in the expected region for the excitation of the S_0 mode. One of the other components is due to the excited transversal wave (see Fig. 2) and is marked with 1 in Fig. 4. The grating lobes marked in Fig. 2 are the source of the third component in the spectra which is marked with 3.

The signal, measured in the plate in front of the transducer, is shown in Fig. 4c where mostly those Lamb mode components are excited for which the dispersion curves coincide with the maxima in Fig. 4b. As a result, we observe mostly S_0 mode in the plate which is expected from the theoretical results shown in Table 1 and from the simulation results presented in Fig. 3.

CONCLUSIONS

The simulation results, presented in this paper, demonstrate the feasibility of applying EFIT to model the Lamb wave propagation in the long specimen. We have discussed the excitation method with the help of a phased array transducer and have applied EFIT to model the generation as well as propagation of Lamb waves in plate like structures. The corresponding simulation results show good agreement with the theoretical as well as the measured results.

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