Numerical modeling and experimental evaluation of geometrical dispersion effects.

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Abstract

For precise acoustic emission (AE) source localization and quantitative AE signal processing it is necessary to analyze signal distortion caused by wave propagation from the source to receiving sensor. Dominant wave modes propagating in thin-walled structures are so called guided waves which exhibit strong dispersion. Experimental determination of the structural impulse response, based on a point source/receiver technique, is necessary to evaluate signal distortion in such structures.

Key words : NDT, modal acoustic emission, laser ultrasonics, guided waves

1 Introduction

Acoustic emission (AE) is a useful tool for detection and identification of material changes in loaded structures. Direct information about AE sources may be distorted by elastic wave propagation through the structure. The detected wavelengths are often comparable to the structure wall thickness. Due to multiple reflections, so called guided (structural) waves are formed. The geometrical dispersion causes uncertainty in wavefront detection and conventional far field wave approach cannot be used to the analysis.

In the presented experimental study of guided wave propagation in thin-wall structures, point-source/point-receiver method has been applied. The pulse laser was used to generate elastic waves in plate-like specimens. Transient waves were recorded by PZT transducers.

Time-frequency analysis of recorded AE signals is improved AE analysis in thin-walled structures.

2 Dispersion effect

Quantitative analysis of a point-like AE source is based on a displacement field expressed by the convolution a source momentum M_{jk} and Green's function G_{ij}, which represents a wave path from source $\mathbf{x}_o$ to receiver $\mathbf{x}$ position, thus

$$u_i(\mathbf{x}, t) = M_{jk} * G_{ij,k}(\mathbf{x}, \mathbf{x}_o; t - t_o). \tag{1}$$

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This approach has an origin in seismology and is introduced in [1]. It may be successively used in case time separated arrival waves, especially when the first wave arrival is not distorted by superposed refracted waves and when the medium may be considered as unbounded. Limitations of the technique appear when we try to analyze the AE signals from plate specimens which thickness is comparable with typical wavelength, [2]. There was measured AE activity from the model of bimaterial interface Epoxy resin/glass.

The dispersion effect may be studied using numerical simulation of acoustical wave, propagated in the medium (Epoxy), in which gradually change lateral boundary. The vertical component of the epicentral impulse response is drawn in Fig.1 and the kinetic energy density distribution in two timeshots over the specimen area may be seen in Fig.2. These results were computed with 2D-FDM program LISA (Local Interaction Simulation Approach), [3]. The plane strain state is considered and thus wavefronts in the snapshots (Fig.2) represent the cross-section of cylindrical wave. The source-receiver distance $r = |\mathbf{x} - \mathbf{x}_o|$ is equal to the epicentral distance `length`=30mm and is permanent. The lateral edge distance (`thickness`) was changed from 30 to 1mm. If the `thickness` is near to `length`, then the wave arrivals are separable. The first arrival represents L-wave delay and its waveform is closed to the shape of 2D Green's function. Second arrival wave is identified as the lateral reflected L-wave and next one is T-wave, converted by refraction of L-wave on the both lateral boundaries (von Schmidt wave). Since the `thickness/length` ratio is less then 0.2, then the multiply refracted wave interference makes wave arrival separation impossible. The delayed new wavefront appears for the ratio less then 0.05 and corresponds to plane stress L-wave. This new waveform has shape of 1D Green's function (plane wave propagation). The same point source : a single force with step time history, was used for all simulations and the all signal changes are caused only by geometrical changes.

Using the AE technique to reveal the material changes (crack, damage, material structure) during processes, we mostly do not avoid waveguide effect. Therefore the modal approach of AE signal processing is adopted.

3 Experimental study of guided waves

The laser source is used to excite wideband mechanical pulse in a material. Different physical processes take place when a solid surface is illuminated by a laser, some of which generate ultrasound. At lower incident power they include heating, generation of thermal waves followed by elastic waves. At higher focused power, material is evaporated from the surface, and a plasma is formed, while the sample may be locally melted, plastically deformed and even the cracks are formed in the absorbing area. Both thermoelastic and ablation mechanism may be used as mechanical pulse source. Its reproducibility depends on laser pulse energy stability, surface material treatment and quality. The main advantage of the laser generated ultrasound is a remote (non-contact) and well reproducible structure excitation. Thermoelastic mechanism is nondestructive, the optical energy absorption may be increased by a glass or liquid layer on the surface. In addition, various source radiation patterns may be formed, and multiple sources may be realized by the light beam splitting.

For our purpose, the ablation-type laser pulses focused into a short line are used to simulate real AE source. The evaporation of additional thin film sprayed on the specimen surface represents single pulse force acting perpendicular to the surface. Such source is independent on substrate material. The film thickness is supposed to be very fine (order 10μm) so that it does not important influence on the surface and guided wave propagation. The experimental setup is described in our contribution at [4].

The grinded carbon steel plate (thickness 5mm) was tested. Frequency dependence of wave velocity caused by thickness represent the dispersive curves, [5], which may be divided into the symmetric (S_0, S_1,...) and antisymmetric (A_0, A_1,...) modes, respectively (see Fig.3). The material wave velocities c_{L} and c_{T} were measured ($c_{\mathrm{L}} = 5.97\mathrm{mm}/\mu\mathrm{s}$, $c_{\mathrm{T}} = 3.27\mathrm{mm}/\mu\mathrm{s}$).

The determination of time differences in AE signals and kinetical energy quantity held in AE event requires the evaluation of the same wavelet (dispersive mode) during wave propagation. The time-frequency representation of a complex time function $s(t)$, determined using Wigner-Ville distribution (WVD), [6]

$$W(t,f) = \int_{-\infty}^{\infty} s(t+\tau/2)s^*(t-\tau/2)\mathrm{e}^{-j2\pi f\tau}\, d\tau \tag{2}$$

helps to distinguish fundamental dispersive modes present in detected signals. Two signals obtained on steel plate at $r = 30.5\mathrm{mm}$ and $90.85\mathrm{mm}$ respectively may be compared in the time, frequency and $t - f$ domain in Fig.4 a) and in Fig.4 b). The amplitude of $t - f$ distribution represents the instantaneous energy of the signal. The frequency dependencies of group delay times, expressed from group velocity as $t_{cg} = r/\mathcal{U}(f)$, are plotted for r =30.5mm and 90.85mm in Fig 5 a), b) and may be compared with WVD. The main form features visible on WVD distributions are in good agreement with the curves of group times t_{cg}. The theoretical results in Fig.5 show complicated structure of the wavefronts. The dominant wavefront carries the most of energy. For small distances r, this wavefront is practically independent on frequency, nevertheless, for larger distances (10 times thickness and more), the influence of mode velocity variations increase, the rise time of the corresponding signal is greater and arrival time determination is more painful.

4 Conclusion

The influence of dispersion effect to AE signal waveform is demonstrated on a simple 2D numerical model. For most AE application the wavelength is comparable with structure thickness and modal AE signal processing technique may be adopted.

Pulse laser Nd:YAG has been used to generate elastic waves in thin-wall structures. The local ablation of the thin film sprayed on the specimen surface modelled point-like or line AE sources independently on the substrate material.

The arrival time detection and amplitude decay evaluation procedures used in AE signal analysis were critically tested. It was shown that attention must be paid when both characteristics are evaluated in dispersive media. In that case, both amplitude decay and arrival time differences must be evaluated from the same wavelet (dispersive mode) observed during the wave propagation. A good correlation between plate dispersion curves and time -frequency representation of detected signals is shown. The $t - f$ distribution techniques seem to be promising in quantitative processing of acoustic emission signals in thin-walled structures.

Acknowledgments

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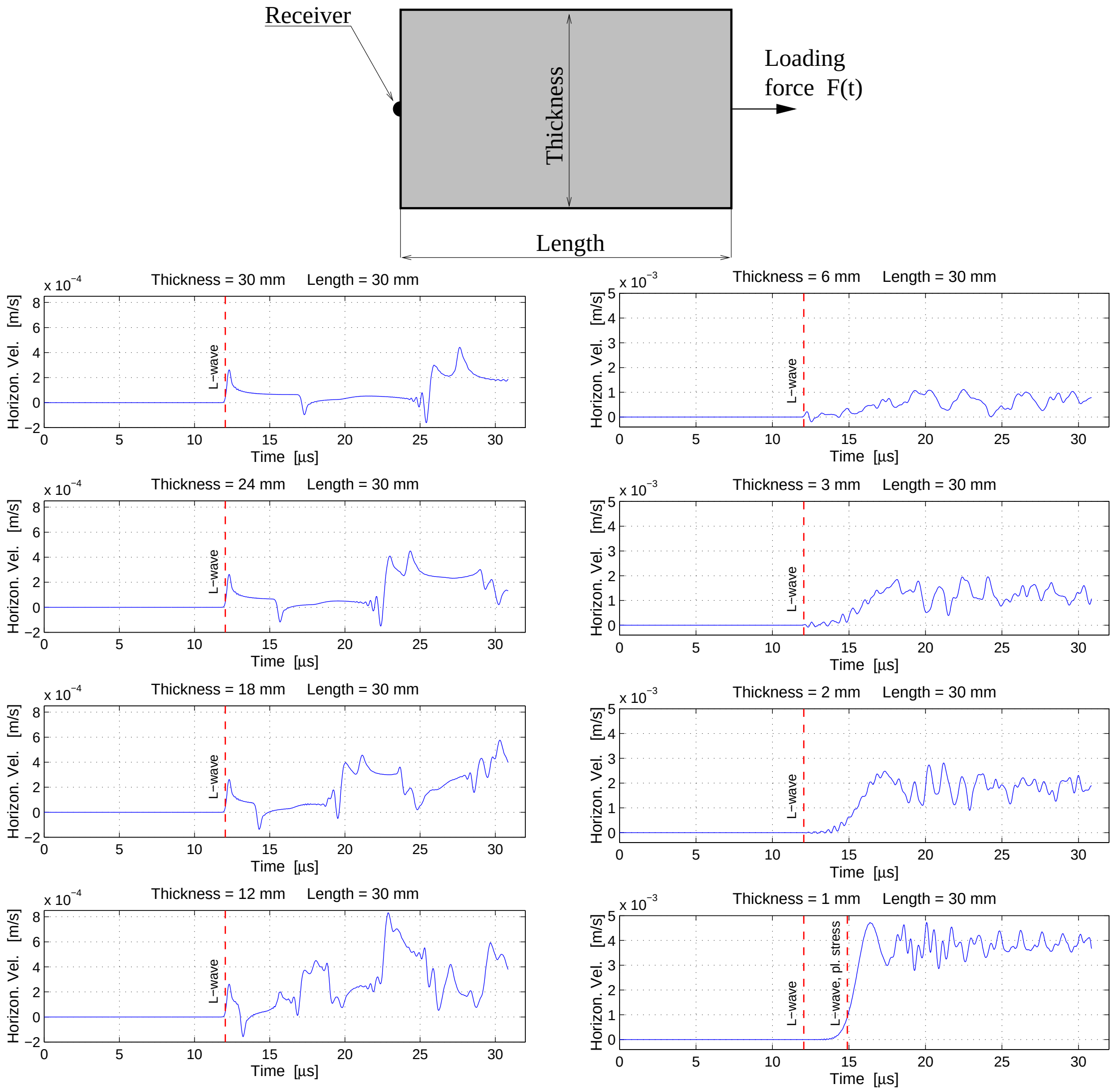

Fig.1 Numerical results : epicentral responses for `thickness/length` ratio decrease, material - Epoxy resin $c_{\mathrm{L}} = 2.49, c_{\mathrm{T}} = 1.13\mathrm{mm}/\mu\mathrm{s}$.

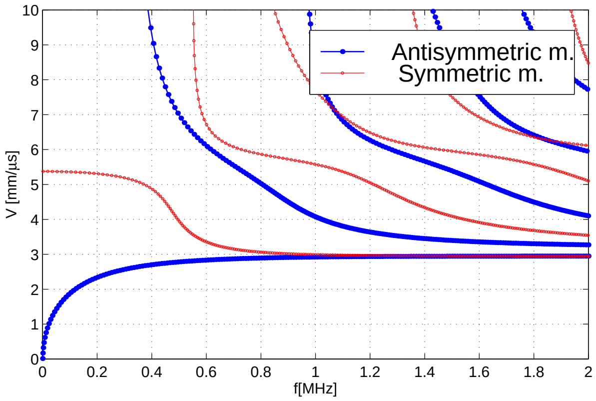

Fig.3 a) Dispersion curves of the carbon steel ($\nu = 0.3$) plate of 5mm thickness : Phase velocity $\mathcal{V}(f)$.

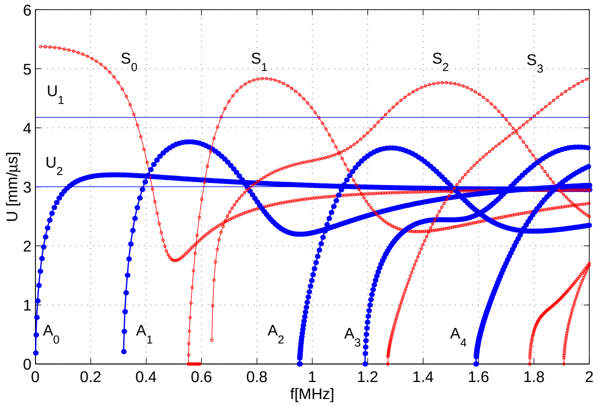

Fig.3 b) Group velocity $\mathcal{U}(f)$, values $\mathcal{U}_1 = 4.17$, $\mathcal{U}_2 = 3.00\mathrm{mm}/\mu\mathrm{s}$ are determined from the first arrival and signal magnitude detection.

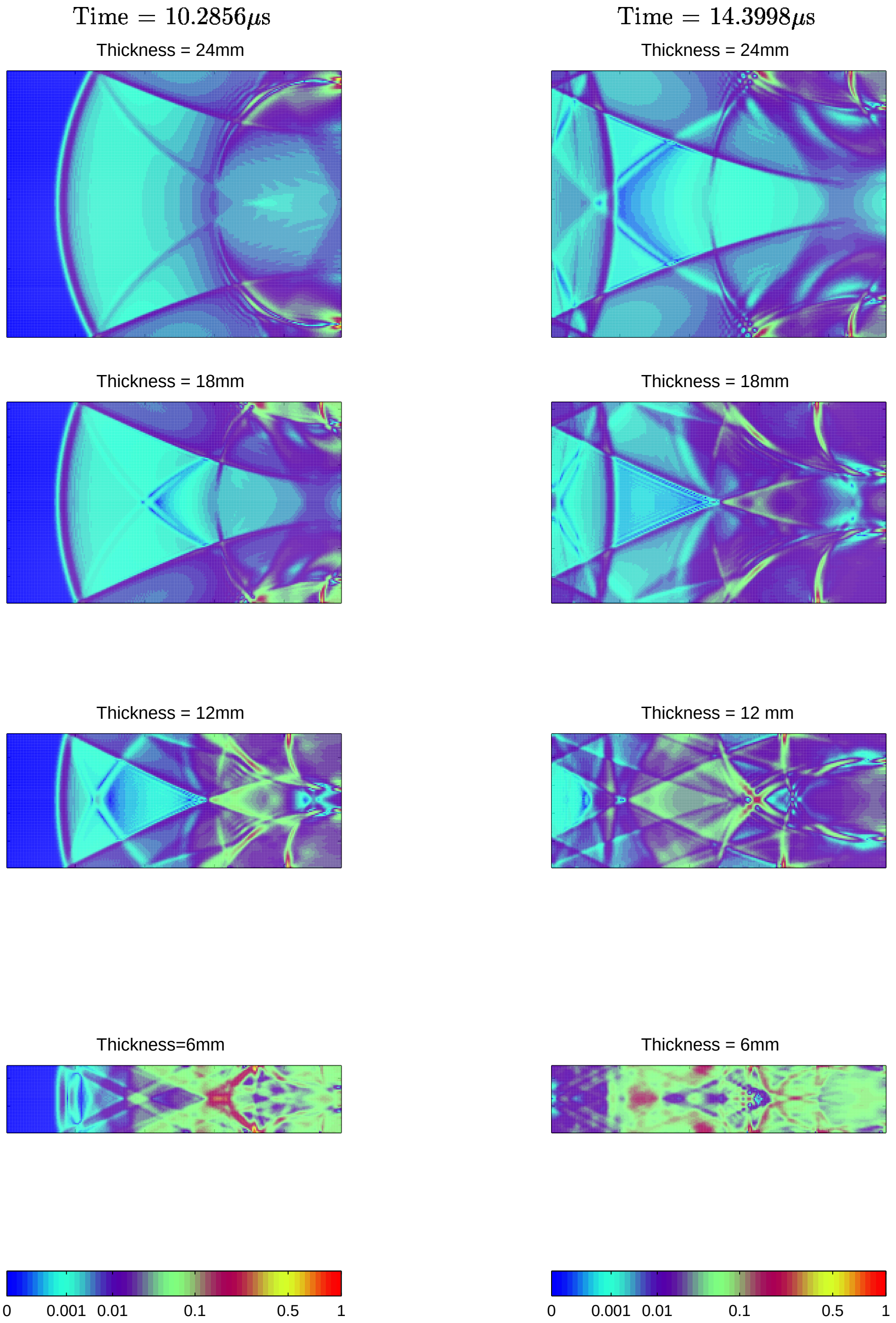

Fig.2 Numerical results : kinetic energy density snapshots for `thickness/length` ratio decrease, material - Epoxy resin $c_{\mathrm{L}} = 2.49, c_{\mathrm{T}} = 1.13\mathrm{mm}/\mu\mathrm{s}$.

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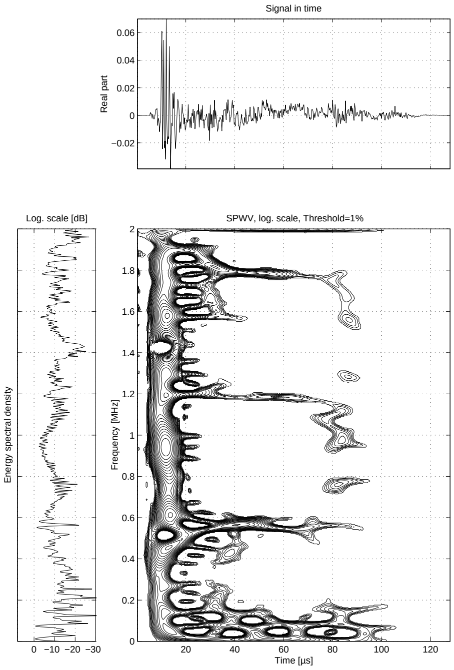

Fig.4 a) Wigner-Ville distribution (SPWV), $r = 30.5$mm.

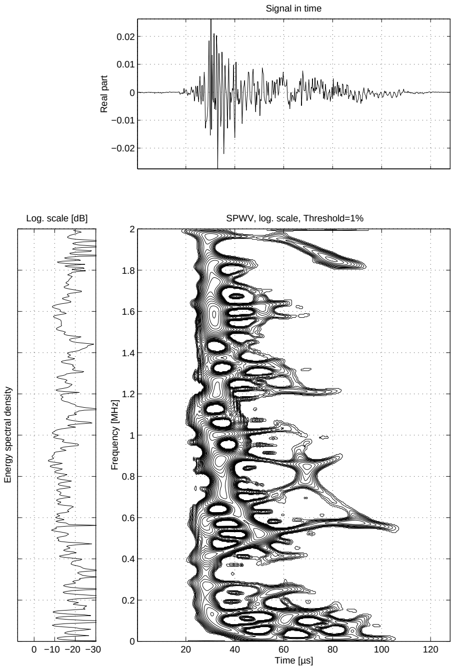

Fig.4 b) Wigner-Ville distribution (SPWV), $r = 90.85$mm.

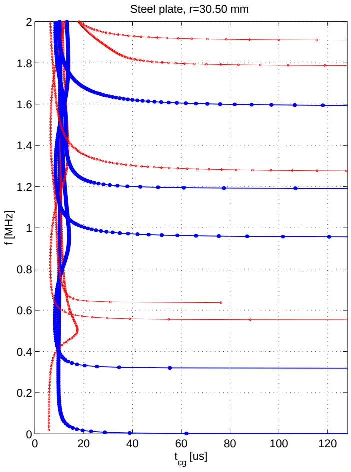

Fig.5 a) $t_{cg} = r/\mathcal{U}$, for $r = 30.5$mm.

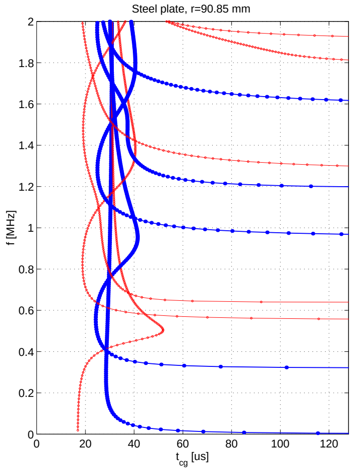

Fig.5 b) $t_{cg} = r/\mathcal{U}$, for $r = 90.85$mm.