PROCESSING OF AE SIGNALS IN DISPERSIVE MEDIA

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ABSTRACT

Acoustic emission (AE) wave propagating in thin wall structure (plate, tube, vessel, etc.) is substantially distorted during its pass from AE source to the transducer. AE signal processing is rather difficult under such conditions (dispersion), and AE source characteristics (location, amplitude, energy, etc.) may be interpreted incorrectly, when signal distortion effects are not considered in the evaluation of source parameters. Wave dispersion effects, i.e. frequency dependence of wave mode velocity, represent the most serious problem in AE signal parameters evaluation. In the paper, construction of guided wave dispersion curves using experimental data is presented. The method, based on wavelet transform, is efficient tool in both isotropic and anisotropic materials, even when current theoretical predictions give no satisfactory results.

KEYWORDS: dispersion curves, wavelet transformation, guided waves

INTRODUCTION

Most of ultrasonic NDT methods are based on monitoring of artificially generated and then received longitudinal or transversal (shear) wave in material [1]. In contrast, the acoustic emission (AE) method uses detection of waves generated by internal AE source in the material, which requires correct location and interpretation. Recently, the guided waves, i.e. waves created by multiple echoes in a thin structure wall, are used in nondestructive testing [2]. The main advantage of guided wave applications is their possibility to detect defects in material on a long distance. The guided waves are dispersion waves, so the wave velocity depends on frequency. Neglecting of the dispersion effects in AE monitoring can lead to relevant mistakes in conclusion about the presence of critical defects in tested structural part.

The application of guided waves in ultrasonic NDT and in evaluation of material properties requires good knowledge of dominant wave modes propagating in a structure, which are characterized by the well known dispersion curves (mostly presented as the dependence of velocity on frequency). To simplify the problem, measurements are usually done with respect to potentiality of one dominant mode wave generation. Signal filtration is also used to emphasize one guided wave mode. Numerical algorithms for the computation of dispersion curves are available for both homogenous plates and composite like structures. Material parameters are the input data in such algorithms. It doesn't represent a problem in a case of homogenous plates manufactured from well-known material, but it could be potential trouble in composite structures. There are often many undetermined factors in composite structures (e.g. precise chemical composition of fillers, stresses in matrix and fibers,

etc.). Material parameters of such structure may vary significantly as a result of complicated manufacturing process. In such situations, the determination of dispersion curves of basic guided modes (s_0, a_0) from experimental data is very useful and even necessary.

The problem of dispersion curves computation from experimental data is not yet completely solved, especially in anisotropic materials. However, two numerical methods are promising:

1. The first method is based on 2-D Fourier transform utilization [5]. The problem of the method is in necessity to record a lot of signals (64 at least, 128 better) from artificial wave sources placed in well-defined points on the structure. Short distance between successive sources (below 1 mm) is advantageous.

2. The second method is based on continuous wavelet transform application [6, 7]. Special wavelets, e.g. Gabor or Morlet wavelet, have well-defined basic frequency. Continuous wavelet transform amplify the frequency in digitized ultrasound wave record, which enables dispersion curve computation of wave mode with highest amplitude.

The second method using continuous wavelet transform will be discussed in this paper. Glass plates are used as a sample of thin-wall structure, as to compare dispersion curves obtained by theoretical and experimental data. Theoretical dispersion curves of guided waves propagating in glass plate are well known.

EXPERIMENT

Laser generated ultrasound is most suitable method for obtaining experimental data. Main advantage of the laser generated ultrasound method is very good reproducibility of ultrasound waves [4].

Nd:YAG pulse laser was used to generate ultrasonic waves. The laser beam was splitted by semipermeable mirror. The first sub-beam has triggered digital oscilloscope, which recorded signals from miniature piezoelectric transducers placed on a glass plate surface. The second sub-beam excited acoustic wave in the plate. The experimental details are described in [4].

Two identical AE transducers were placed on opposite sides in the plate center. Using this transducer configuration, along with accurate synchronization of oscilloscope channels enables symmetric or antisymmetric guided waves modes emphasizing in recorded signals. Sum of both recorded signals results in signal with emphasized symmetrical modes, and the signal difference emphasizes antisymmetric modes of guided waves (see fig. 1).

CONTINUOUS WAVELET TRANSFORMATION

Continuous wavelet transform (CWT) is a kind of time-frequency transform defined by the formula

$$Wf(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \Psi^* \left(\frac{t-b}{a} \right) \mathrm{d}t, \qquad (1)$$

where a is scale parameter and b is time. Ψ is a wavelet and f is transformed function. Symbol * represents complex conjugate value. The wavelet transform is used to identify hidden signal properties, such as small discontinuities, frequency changes and transient effects. Reciprocal scale parameter a has a meaning of frequency in intuitive

sense, but the wavelet Ψ is usually not the periodic function, so it has no frequency in mathematical sense. Fortunately, there exist also wavelets based on periodic functions with well-defined frequency.

Morlet wavelet (fig. 2) is an example of the periodic function based wavelet. It is given by formula

$$\Psi(x) = e^{-x^2/2} \cos(5x), \tag{2}$$

which represents product of attenuation term $\exp(-x^2/2)$ and periodic term $\cos(5x)$.

If the function f is digitised AE signal with sampling frequency F, then $f(t)$ is real and the function is represented by its discrete values f_n. In addition Morlet wavelet frequency expressed using scale parameter a is

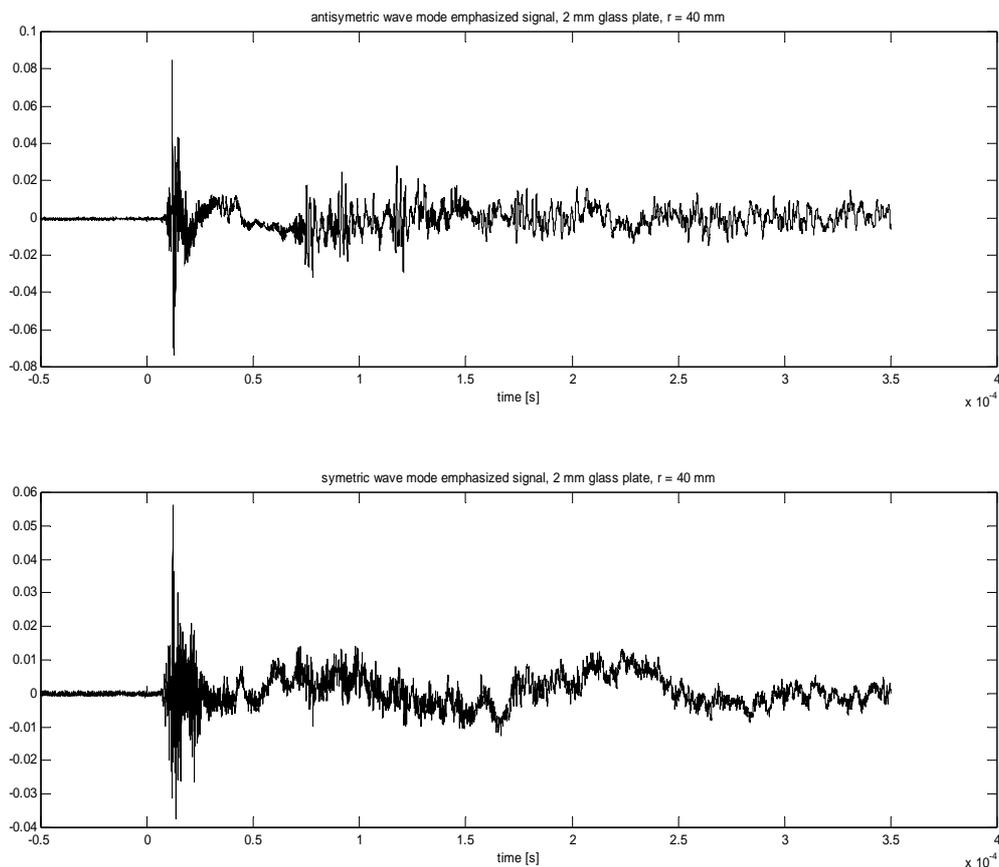$$F_\Psi(a) = \frac{5}{2\pi a} F. \tag{3}$$

Figure 1: Acoustic wave with symmetric or antisymmetric wave modes emphasized
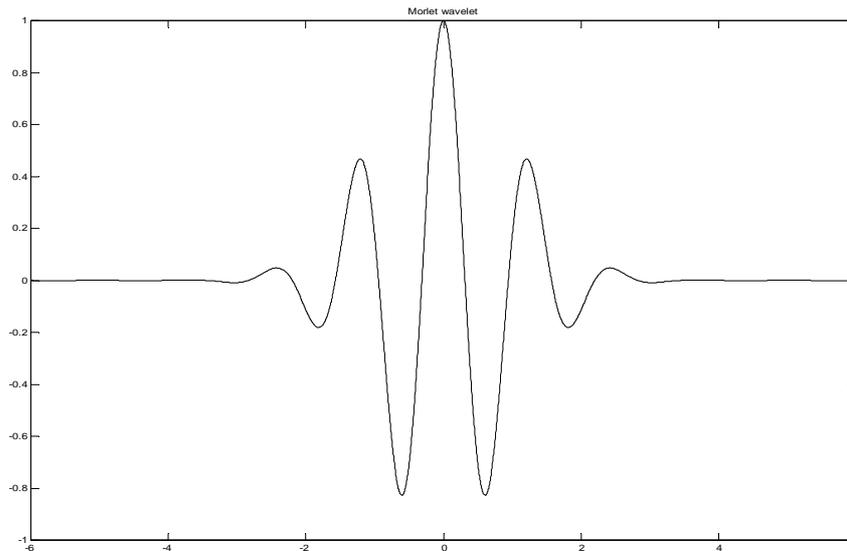
Figure 2: Morlet wavelet

COMPUTATION OF DISPERSION CURVES

Continuous wavelet transform $Wf(a,b)$ of digitised signal using Morlet wavelet is a signal with highlighted $F_\psi(a)$ frequency (see formula (3)). Because guided wave amplitude is mostly rather high (especially the amplitude of first guided wave modes a_0, s_0), the waves arrivals are well perceptible in CWT signals. Using guided wave arrival time (detected in transformed signal) and acoustic wave source – transducer distance, the wave velocity is computed and point on dispersion curve with frequency $F_\psi(a)$ is known. Dispersion curve is then sampled by changing the scale parameter a.

Some potential troubles are connected with the algorithm application. The first problem is in wave arrival time detection. The arrival time is given by corresponding wave package maximum (see upper part of the fig. 3). But it is not always easy to determine the maximum. Solution of the problem is in using of Hilbert transform (bottom part of the figure 3). That transform represents the signal envelope where the wave package maxima are evident. The second problem, illustrated in fig. 4, is interaction of guided wave modes. First part of the fig. 4 shows transformation of signal with emphasized antisymmetric wave modes. Maximum, which corresponds to a_0 wave mode, is obvious. On the other hand, the maximum corresponding to s_0 wave mode is overlapped by the a_0 maximum (bottom part of fig. 4), although the signal with emphasized symmetric modes was used. To solve the problem partially, filtration of original signal and/or the use of selected signal is suggested.

It is well known that the spectra of symmetric and antisymmetric mode guided waves differ substantially [8]. That property is illustrated in fig. 5, where the normalized spectra of signals with emphasized symmetric or antisymmetric wave modes are plotted. Antisymmetric guided wave modes contain much more of low frequencies than the symmetric ones. Band-pass filtering is often used to separate both symmetric and antisymmetric wave modes. But this procedure is not suitable for the above described dispersion curves construction algorithm. To obtain the whole
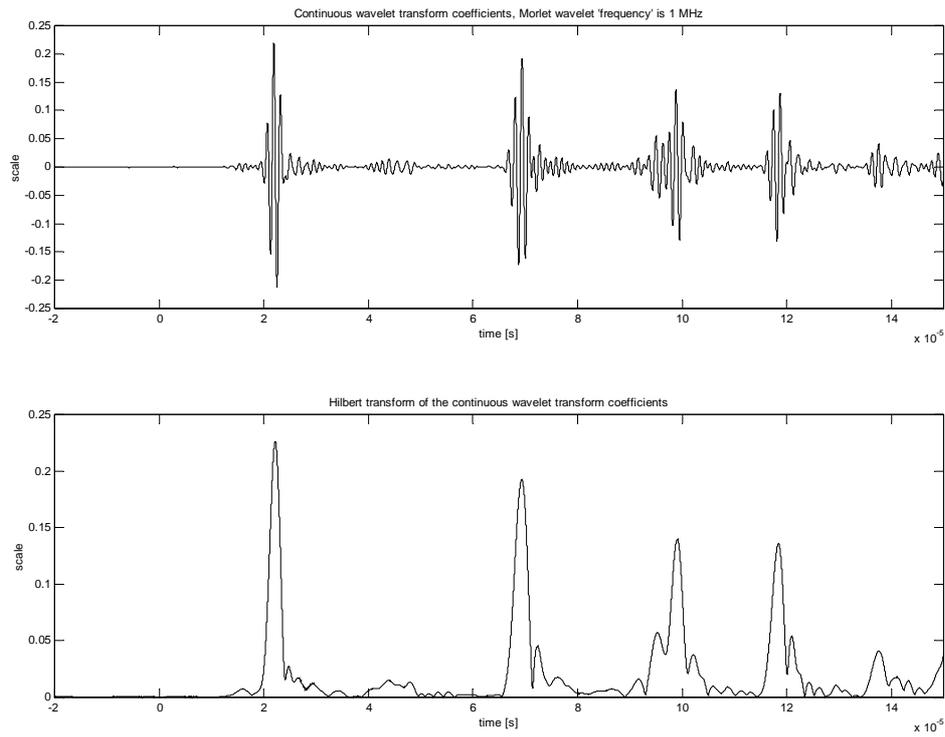
Figure 3: Continuous wavelet transform of acoustic wave (Morlet wavelet is used) and the signal after Hilbert transform
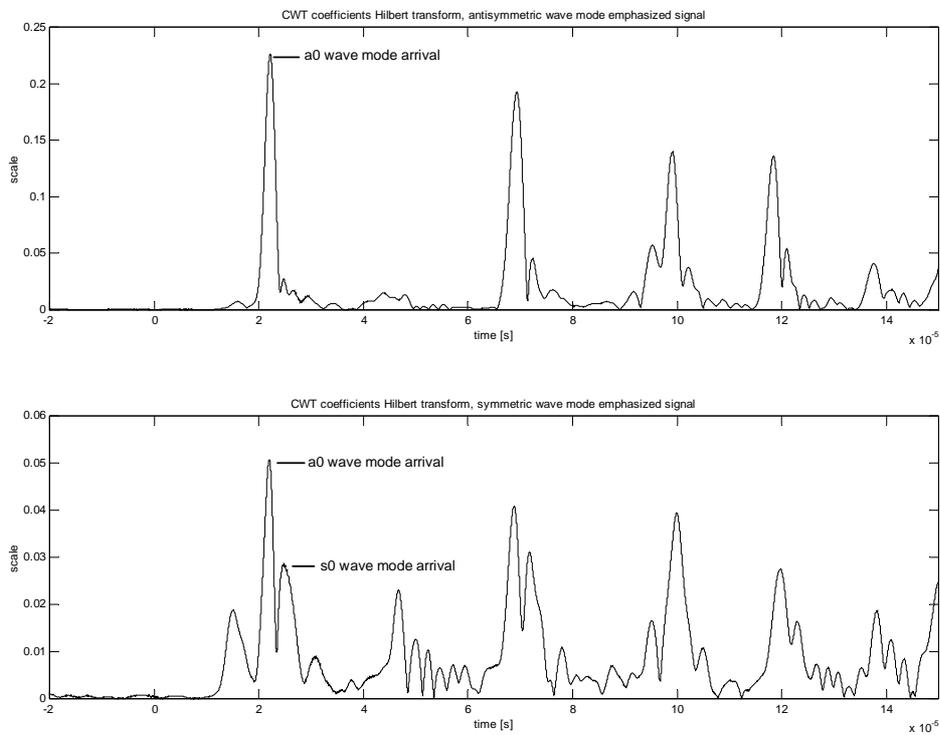

Figure 4: CWT coefficients transformed using Hilbert transform. Original signal had antisymmetric or symmetric wave modes emphasized

dispersion curve, we need all frequencies contained in the signal. If set of plates with different thicknesses is available, more thick plate looks better when we compute symmetric wave modes dispersion curves. But the key factor is still proper maximum selection in the transformed signal (see fig. 4).

Outputs of the described algorithm – a_0 and s_0 wave modes dispersion curves in glass plate – are plotted in figures 6 and 7. The a_0 wave mode dispersion curve is obtained quite easily (see fig. 6). Difference between theoretical and computed dispersion curve is negligible. Small divergence may cause AE transducer size; there is not obvious the source - transducer distance. On the other hand, symmetric wave mode (s_0) dispersion curve computation comes to relatively tough problem (fig. 7). Finally we used the 8 mm thick glass plate, because there it is easier to obtain the curve than in a case of 2 mm thick plate. No original signal filtration is applied. Difference between theoretical and computed curve is now bigger, but the shape of curves is similar. The results of described algorithm are perfect for higher frequencies (above 600 kHz), as it was expected.
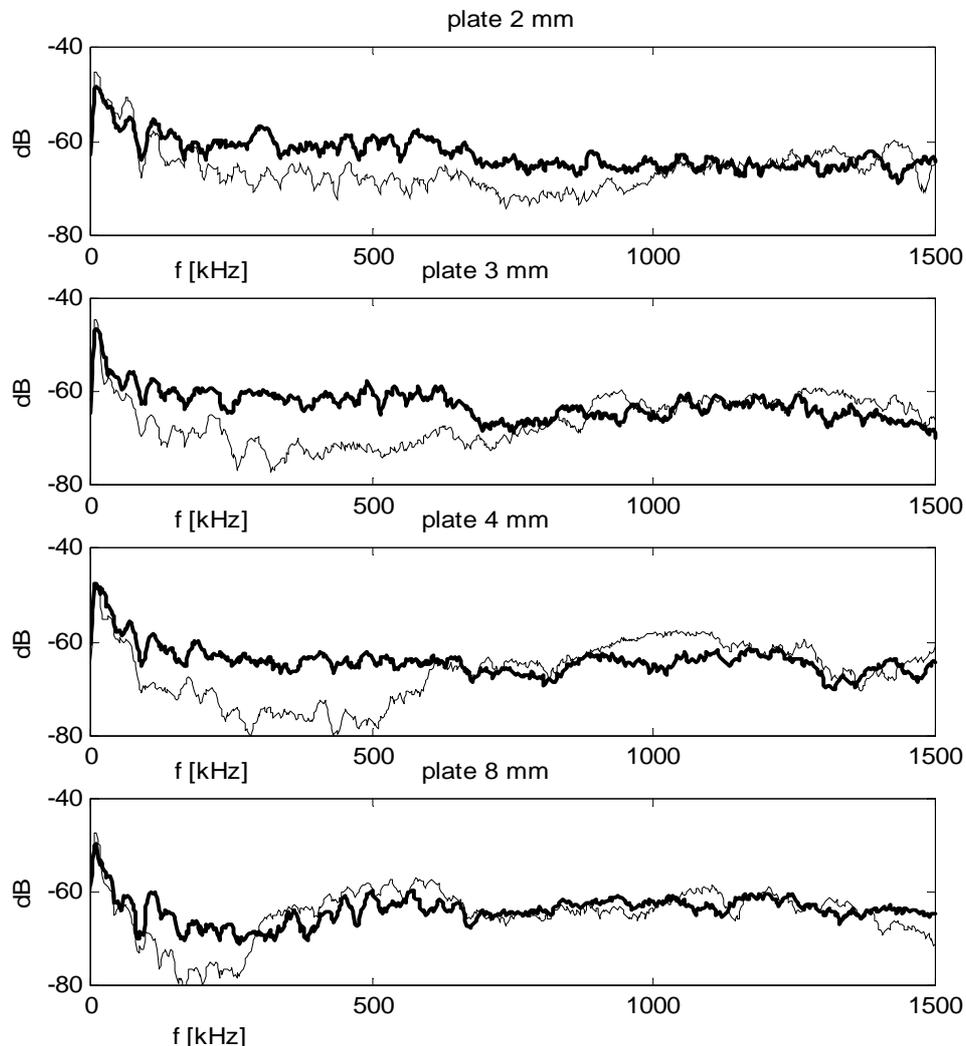

Figure 5: Spectra sum (thin line) and difference (thick line) of AE signals. The signals were recorded from two transducers placed on opposite plate sides.
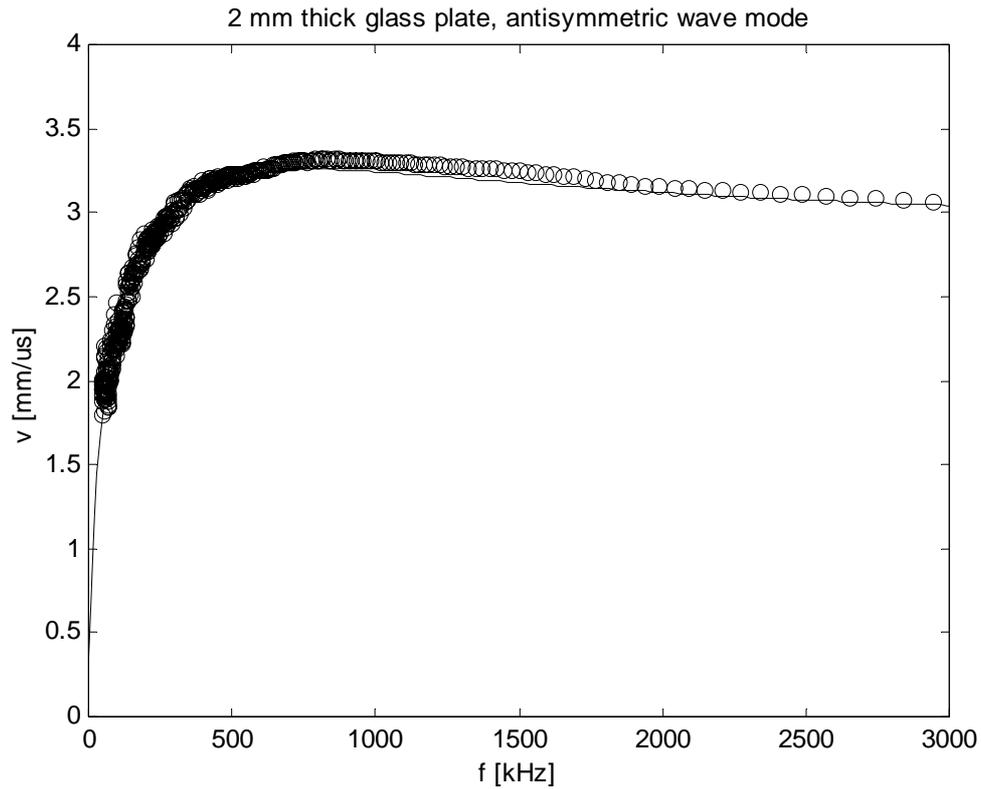
2 mm thick glass plate, antisymmetric wave mode

Figure 6: a_0 wave mode dispersion curve in 2 mm thick glass plate. Theoretical curve is plotted using solid line, curve computed from experim. data is plotted using circles
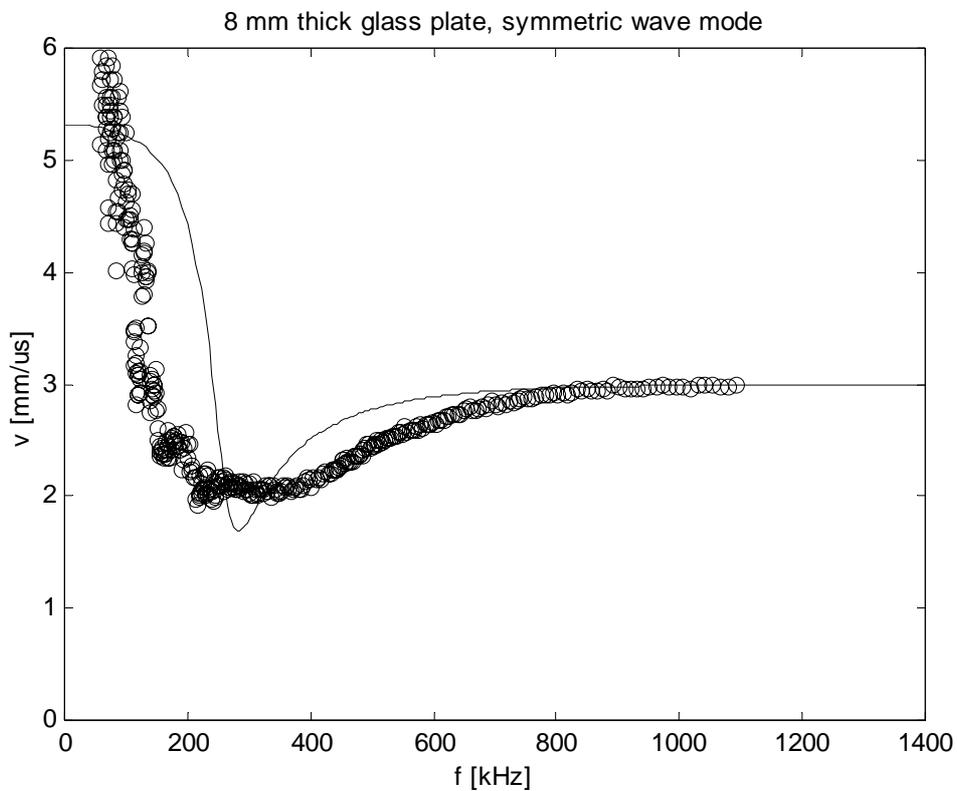
8 mm thick glass plate, symmetric wave mode

Figure 7: s_0 wave mode dispersion curve in 8 mm thick glass plate. Theoretical curve is plotted using solid line, curve computed from experim. data is plotted using circles

COMPUTATION OF DISPERSION CURVES IN POLYMER SAMPLES

To demonstrate wavelet algorithm potential and limits, data from tensile tests of polymer samples was used as algorithm input data. $100 \times 10 \times 4$ mm polymer samples were used in the experiment. The samples were manufactured from pure polyethylene (PE), pure polypropylene (PP), from 50%/50% PE/PP blend and from blend of PE, PP and additive VISTALON. Tensile tests of PP and its blends with PE and VISTALON have been recorded by digital camcorder. Acoustic emission (AE) was monitored during tests by two transducers attached to test samples, allowing linear location of AE sources. The sources were recorded using transient recorder ADAM-MAURER (fig. 8c), 8d)), AE parameters during test by digital analyzer DAKEL-XEDO (fig. 8b)). Tested materials exhibit large localized plastic deformation – necking – reaching from tens to hundreds of percent before failure. Dispersion waves play significant role in complex wavefield observed in the samples, so dispersion curves knowledge improves significantly conclusions about AE events and sources and finally about tested polymer sample damage process.

Described wavelet algorithm result, using AE signal from fig. 8d) as the algorithm input data, is shown in figure 9. Dispersion curve of wave mode with the highest amplitude was computed only. The reason is tensile test configuration. AE transducers position didn't enable symmetric and antisymmetric wave modes
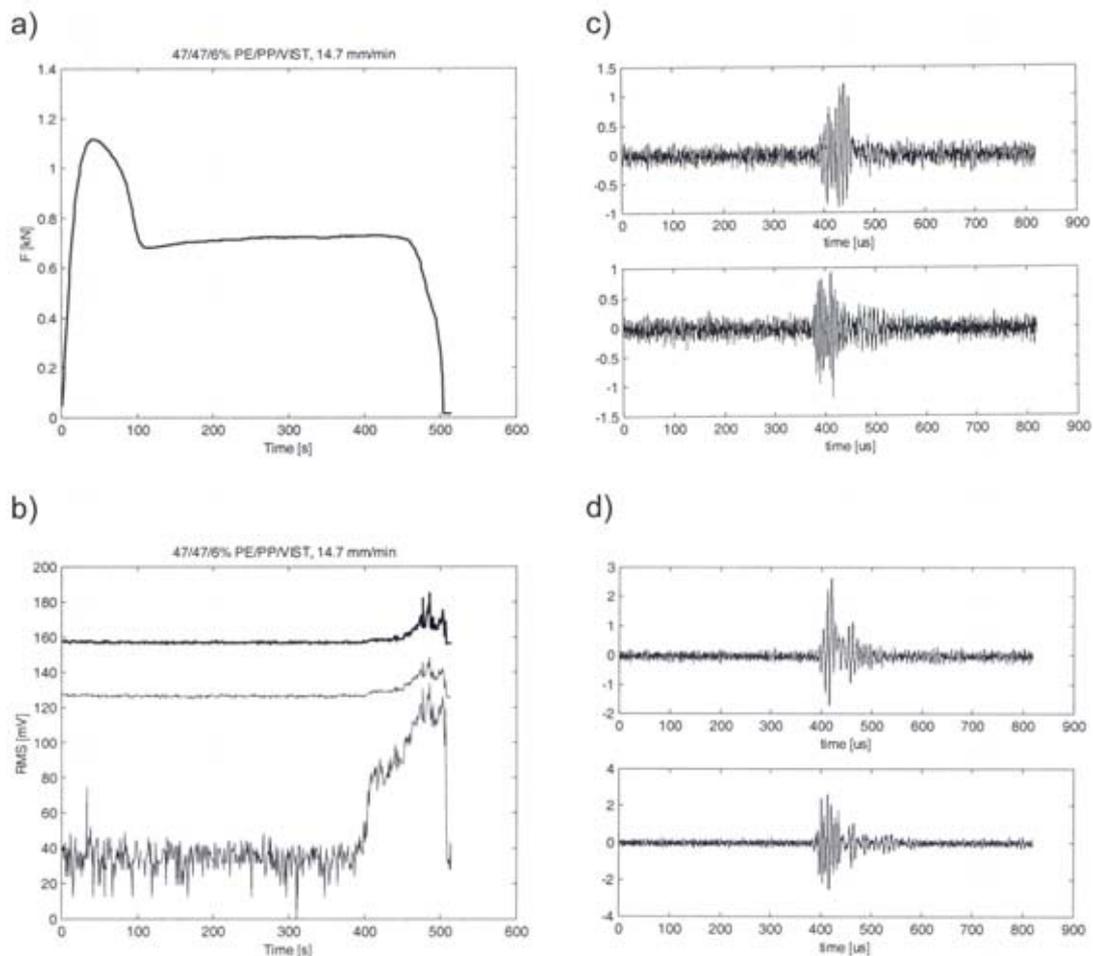

Figure 8: PE/PP/VISTEON sample tensile test: a) diagram of loading force, b) AE activity monitoring using RMS and two levels of counts, c), d) recorded AE events
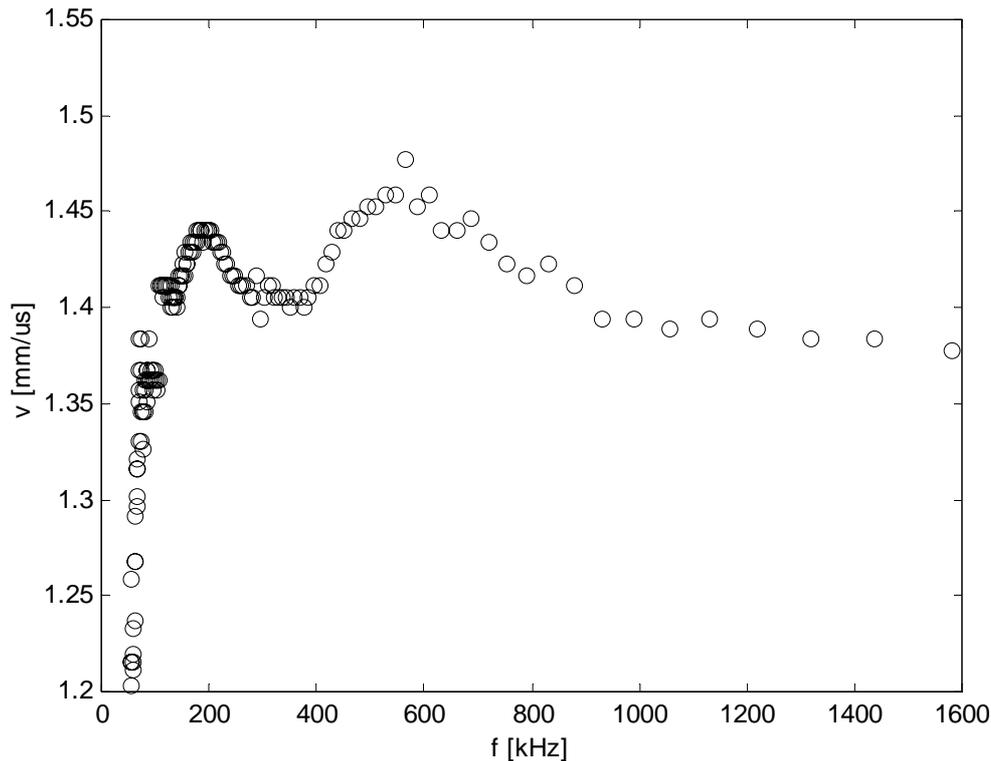
Figure 9: a_0 wave mode dispersion curve approximation in 4 mm thick
PE/PP/VISTALON polymer sample. Recorded AE event from
figure 8d) was used as algorithm input

emphasizing in the similar way as above (see fig. 1). Moreover recorded signals have indispensable noise level, although only the best signals (see fig. 8) were utilized.

The difficulties (background noise, dispersion wave modes interaction) affect a_0 wave mode dispersion curve approximation (fig. 9). There are visible some discontinuities and drapes in fig.9. However, despite really unfavourable experiment conditions, the wavelet algorithm gives important result applicable for investigation of polymer samples damage process.

CONCLUSION

Dispersion curves of basic guided waves modes (a_0, s_0) in glass plates were computed using the experimental data. The computational algorithm is described, which is based on continuous wavelet transform. Signals recorded during the experiments with laser-generated ultrasound were used as input data in the algorithm. Advantages of laser-generated ultrasound are very good reproducibility of the wave source and the exact source positioning, which are important conditions for reliable algorithm application.

Some additional steps were done as to improve the computation of dispersion curves. The first improvement of the wavelet transform based algorithm is in the Hilbert transform utilization. The guided wave mode arrival time is much more evident in Hilbert-transformed signal. The second step is the use of glass plates different thickness. The reason of that is to increase specific wave mode fraction in the complex signal. The same purpose had a special experimental configuration using the pair of piezoelectric transducers placed on opposite sides of at the center of tested

plate. Such configuration along with precise synchronization of recorder channels enables emphasizing of symmetric or antisymmetric guided waves modes in signal.

Described CWT based algorithm is useful tool for the computation of dispersion curves of main guided wave modes (a_0, s_0). The algorithm was tested using glass plates mainly, but it can be used in other situations, e.g. in polymer samples damage process investigation.

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