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

1. 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.

2. Experiment

Laser generated ultrasound is most suitable method for obtaining experimental data. Main advantage of the laser generated ultrasound method is good reproducibility of ultrasound waves [4]. Nd:YAG pulse laser was used to generate ultrasonic waves. The laser beam was split by semi-permeable 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 given 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 anti-symmetric guided waves modes emphasis in recorded signals. Sum of both recorded signals results in signal with emphasized symmetrical modes, and the signal difference emphasizes anti-symmetric modes of guided waves (see Fig. 1).

3. Continuous Wavelet Transform

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

\[ Wf(a,b) = \frac{1}{a} \int_{-\infty}^{\infty} f(t) \Psi^* \left( \frac{t-b}{a} \right) dt, \]

where \( a \) is scale parameter and \( b \) is time. \( \Psi \) 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 \( \Psi \) 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

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

which represents product of attenuation term \( \exp(-x^2/2) \) and periodic term \( \cos(5x) \).
If the function $f$ is a 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

$$F_\psi(a) = \frac{5}{2\pi a} F.$$  \hspace{1cm} (3)

---

Fig. 1  Acoustic waves with symmetric (top) or anti-symmetric (bottom) wave modes emphasized. Each division = 10 mV and 50 µs.

Fig. 2  Morlet wavelet
4. 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 equation (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 AE 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 packet maximum (see upper part of Fig. 3). But it is not always easy to determine the maximum. Solution of the problem is in the use of Hilbert transform (bottom part of Fig. 3). That transform represents the signal envelope where the wave packet maxima are evident. The second problem, illustrated in Fig. 4, is interaction of guided-wave modes. First part of Fig. 4 shows transformation of signal with anti-symmetric wave modes emphasized. 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), even though the signal with symmetric modes emphasized 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 anti-symmetric mode guided waves differ substantially [8]. That property is illustrated in Fig. 5, where the normalized spectra of signals with emphasized symmetric or anti-symmetric wave modes are plotted. Anti-symmetric guided wave modes contain much more of low frequencies than the symmetric ones. Band-pass filtering is often used to separate both symmetric and anti-symmetric wave modes. But this procedure is not suitable for the above described construction algorithm of dispersion curves. To obtain the whole dispersion curve, we need all frequencies contained in the signal. If set of plates with different thicknesses is available, a thicker plate looks better when we compute the dispersion curves of symmetric wave modes. 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 Figs. 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 be caused by AE transducer size; there is no obvious effect of the source - transducer distance. On the other hand, symmetric wave mode ($s_0$) dispersion curve computation encounters relatively tough problem (Fig. 7). Finally we used the 8-mm thick glass plate, because 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.

5. 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
Fig. 3 Continuous wavelet transform of AE wave (Morlet wavelet is used) and the signal after Hilbert transform. Time scale = 20 µs per division.

Fig. 4 CWT coefficients transformed using Hilbert transform. Original signal had anti-symmetric or symmetric wave modes emphasized. Time scale = 20 µs per division.

(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, d), AE parameters were also recorded during test by digital analyzer DAKEL-XEDO (Fig. 8b). Tested materials exhibit large localized plastic deformation – necking
Fig. 5 Spectra sum (thin line) and difference (thick line) of AE signals. The signals were recorded from two transducers placed on opposite plate sides.

Fig. 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 – reaching from tens to hundreds of percent before failure. Dispersion waves play significant role in complex wave field observed in the samples, so the knowledge of dispersion curves improves significantly conclusions about AE events and sources and finally about tested polymer sample damage process.
Fig. 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

Described wavelet algorithm result, using AE signal from Fig. 8d as the algorithm input data, is shown in Fig. 9. Dispersion curve of wave mode with the highest amplitude was computed only as this is tensile test configuration and AE transducer positions did not allow the emphasis of symmetric and anti-symmetric wave modes in the similar way as in Fig. 1. Moreover recorded signals have background noise, 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 unfavorable experimental conditions, the wavelet algorithm gives important result applicable for damage-process investigation of polymer samples.

6. 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 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 of 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 at the center of tested plate. Such configuration along with precise synchronization of recorder channels enables the emphasis of symmetric or anti-symmetric guided-waves modes in signal.
Fig. 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.

Fig. 9 $a_0$-wave mode dispersion curve approximation in 4-mm thick PE/PP/VISTALON polymer sample. Recorded AE event from Fig. 8d) was used as algorithm input.
Described CWT-based algorithm is a 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 damage process investigation of polymer samples.

Acknowledgement

The present research is supported by the Grant Agency of Czech Republic under the grant No. 201/04/2102 and grant No. 205/03/0071. The Czech Society for NDT is also acknowledged for supporting participation of the first author at the conference.

References