APPLICATION OF WAVELET TRANSFORM IN ANALYSIS OF GUIDED WAVE PROPAGATION SIGNALS FOR DAMAGE DETECTION IN A STEEL PLATE

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Summary

The paper presents results of experimental investigations on damage detection using guided wave propagation technique. The tested specimen was a steel plate with a defect in the form of a rectangular notch. Lamb waves were excited by a PZT actuator and sensed by a laser vibrometer. Since reflections from damage in registered signals are often masked by measurement noise, for identification of time of reflections from damage, continuous wavelet transform (CWT) was used. Obtained results indicated that application of wavelet signal processing enabled precise reconstruction of reflected wavefront from damage.

Keywords: guided waves, damage detection, non-destructive testing, continuous wavelet transform

ZASTOSOWANIE TRANSFORMATY FALKOWEJ W ANALIZIE SYGNAŁÓW FAL PROWADZONYCH DLA CELÓW DETEKCJI USZKODZEŃ W PŁYCIE STALOWEJ

Streszczenie

W artykule przedstawiono wyniki badań doświadczalnych dotyczących detekcji uszkodzeń za pomocą metody propagacji fal prowadzonych. Badania przeprowadzono na stalowej płycie z uszkodzeniem w formie prostokątnego nacięcia. Fale Lamba zostały wzbudzone przy użyciu piezoaktuatora, zaś do pomiaru przebiegów czasowych zastosowano wibrometr laserowy. Ponieważ odbicia propagującej fali od uszkodzenia często bywają maskowane przez szum pomiarowy, do identyfikacji czasu odbicia zastosowano ciągłą transformatę falkową. Otrzymane wyniki wskazują, że przetwarzanie sygnałów pomiarowych fal prowadzonych za pomocą transformaty falkowej umożliwiło precyzyjną rekonstrukcję frontu fali odbitego od uszkodzenia.

Słowa kluczowe: fale prowadzone, detekcja uszkodzeń, diagnostyka nieniszcząca, ciągła transformata falkowa

1. INTRODUCTION

The process of damage detection is the first step in more general diagnostic process, which determines further decisions connected with monitoring or repairing an engineering structure. The main objective of non-destructive diagnostic methods is to detect fault in its early stage of development and therefore appropriate interpretation of registered data is necessary. The usefulness of the phenomenon of guided wave propagation in monitoring of the occurrence and development of damage has been the concern of many previous works (e.g. [1-4]). In general, the diagnostic process using guided wave propagation is based on registering time signals and appropriate interpretation of recorded disturbances occurring in the form of amplitude changes. One of the most important advantages of the guided wave technique is the ability to propagate over long distances and large areas with small energy loss resulting in small decrease of the amplitude of the propagating wave packet, which allows for obtaining results relatively simple to interpret [5]. However, despite this benefit, there are numerous problems associated with the acquired signals of propagating waves. The clarity of results depends on the type of detected damage, its shape, size and orientation with respect to the sensor [6]. Therefore, it is common to use various signal processing techniques which have become an essential part of damage detection process. One of them is the wavelet transform which is used to obtain time-frequency representation of analysed signals. Since two decades, wavelet analysis has generated much interest in various engineering applications, especially in non-destructive testing (e.g. [7-10]).

In this paper an experimental investigation of guided wave propagation in the context of diagnostics of a steel plate structure is presented. Damage detection is based on time domain Lamb wave signals and the observation of changes in registered waveforms. For precise identification of time of reflections from damage, time-scale analysis with the use of wavelet scalograms is performed. The effectiveness of the proposed wavelet-based procedure is examined by the reconstruction of the shape of the reflected wavefront.

2. EXPERIMENTAL INVESTIGATIONS

2.1. Geometry of tested specimen

Wave propagation measurements were conducted for a steel plate with dimensions of 1000 mm × 1000 mm and thickness of 5 mm (Fig. 1). The experimentally determined material parameters, i.e. the mass density, the modulus of elasticity and the Poisson's ratio, were equal to: 7872 kg/m^3, 205.35 GPa and 0.28, respectively. Damage in the plate was introduced as a rectangular notch with a depth of 2.5 mm and dimensions of 250 mm × 12.5 mm. Such type of defect can represent corrosion damage which often occurs in civil or mechanical engineering structures.

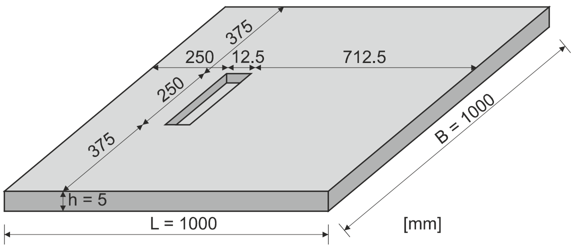

Fig. 1. Geometry of tested steel plate with damage

2.2. Experimental set-up

The photo of the experimental set-up is shown in Fig. 2. Lamb waves were generated by the piezoelectric actuator CMAP11 manufactured by Noliac. Excitation was in the form of a wave packet consisting of five cycles of sine wave modulated by the Hanning window. The carrier frequency of wave was 150 kHz. The wave packet was delivered to the piezoelectric actuator by the use of the function generator and the high-voltage amplifier. Wave propagation signals (velocity components perpendicular to the surface of the plate) were recorded by means of the laser vibrometer Polytec PSV-3D-400-M.

2.3. Configuration of measurement points

One spatial configuration of points (in which Lamb waves were excited and registered) was considered during the experiment (Fig. 3). The input signal was generated in one point labelled with letter A and waves were sensed in eight points labelled with numbers 1 to 8. Measurement points of numbers 1 to 7 were distributed along a straight line. The configuration with several sensing points located along the line is one of the simplest arrangements and it enables precise reconstruction of wavefront reflected from damage of considerable length. For such line configuration of registration points, detection of damage in any form (long notch, hole, etc.) gives two equivalent solutions, which are symmetric with respect to the axis, on which sensors lie [11]. Therefore in the present study one additional point of number 8 was introduced. It was shifted with respect to the strip of measurement points of numbers 1 to 7. The shifting was necessary for unambiguous identification of the location of damage. A difference in the time-of-flight (ToF) for reflection from damage registered in signals for points 8 and 7 was taken into account to determine the direction from which the reflected wave propagated.

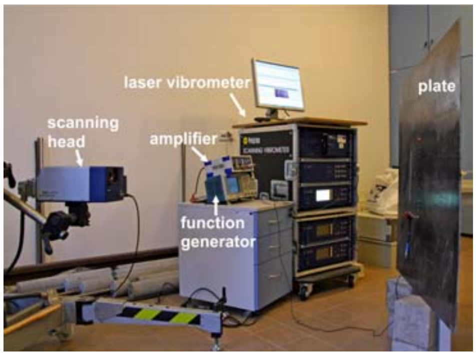

Fig. 2. Experimental set-up

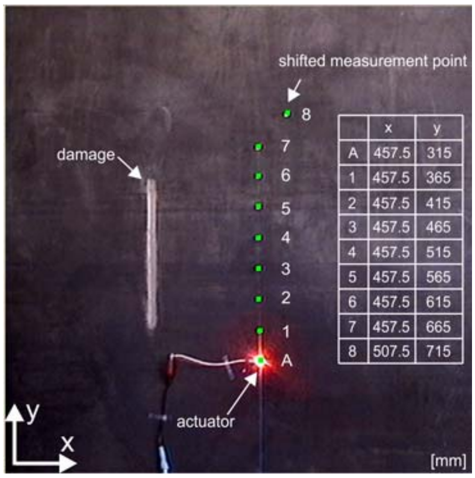

Fig. 3. Configuration of measurement points on tested steel plate

2.4. Experimental results

Experimental results in the form of time domain velocity signals are presented in Fig. 4. A location of damage was intended to calculate based on the value of the velocity of propagating waves and the time-of-flight between the incident wave and the wave scattered by damage. Even though damage in the tested plate was significant and situated close to the group of measurement points, the amplitude of the reflection from damage was comparable to the measurement noise for a lot of registered signals. Thus, there was a considerable difficulty in identifying the location of damage. For precise determination of damage position, a signal processing based on the wavelet transform was proposed. For each signal reflections from damage were identified and indicated using the procedure described in the following part of this paper.

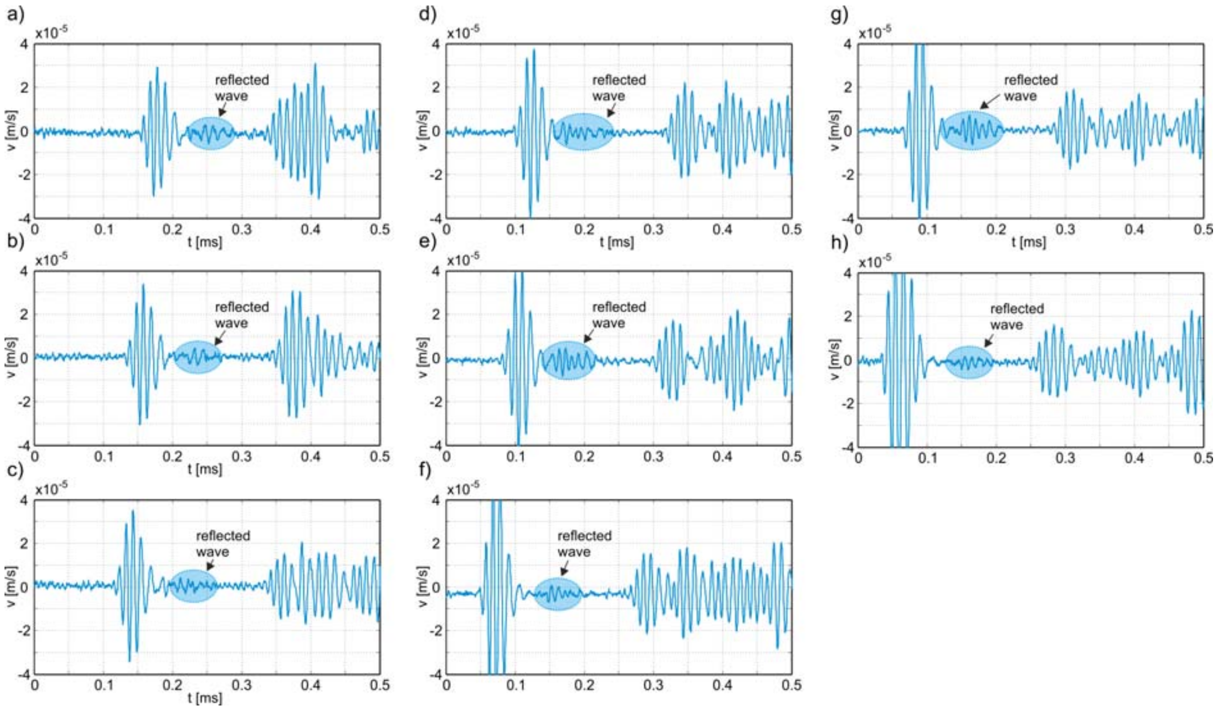

Fig. 4. Set of wave propagation time signals recorded at:
a) point 8, b) point 7, c) point 6, d) point 5, e) point 4, f) point 3, g) point 2, h) point 1

3. SIGNAL PROCESSING BY CONTINUOUS WAVELET TRANSFORM

3.1. Outline of continuous wavelet transform

During this investigation one of the most important features of wavelets has been used, namely their ability to provide a time-scale representation of a signal characterized by variable-sized regions. Owing to this time-scale view, the wavelet transform enables to extract discontinuities containing in a signal.

For a given signal $v(t)$, where t denotes a temporal coordinate, a continuous wavelet transform can be defined as the inner product of a signal function and with wavelet functions [12]:

$$Wf(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} v(t)\psi^*\left(\frac{t-b}{a}\right) dt\,, \qquad (1)$$

where the real numbers a and b denote scale of real or complex-value function $\psi(t)$, called the mother wavelet and translation parameters, respectively. $\psi^*(t)$ is the complex conjugate to the wavelet function and Wf is called a wavelet coefficient.

In this study, a Morlet wavelet was used as the mother wavelet. The Morlet wavelet is the product of a harmonic wave and a Gaussian window and it can be described by (e.g. [13, 14]):

$$\psi(t) = Ce^{-\frac{x^2}{2}} \cos(Dx)\,, \qquad (2)$$

where C and D are constant. For signal processing of propagating Lamb waves, the Morlet wavelet implemented in MATLAB® was used with parameters $C=1$ and $D=5$ [14].

3.2. Wavelet analysis of Lamb waves

In general, damage detection algorithms based on guided wave propagation use the group velocity of propagating waves and the time-of-flight between the incident wave and the wave scattered by damage. However, in the case of small damage or damage located far away from the group of sensing points the amplitude of the scattered wave can be not high enough to indicate additional reflections. Another problem concerning the readability of results is material and geometrical damping. The energy of every wave dissipates with the distance from the source. This phenomenon in known as the attenuation, manifesting as the gradual reduction in the magnitude of wave signals [10].

In this section, a wavelet procedure dedicated for calculation of the time-of-flight between the arrival of incident wave and the wave reflected from damage is presented. Figure 5a shows the signal registered at point 6. One can see that the wave packet reflected from damage was not distinct and for this case precise determination of the time-of-flight was not possible.

The first step of the procedure was the transformation of a time signal into two-dimensional time-scale space by means of the continuous wavelet transform. Figure 5b gives the scalogram which illustrates the values of individual wavelet coefficients depending on the scale and time. In general, when the section of the signal has the same shape as the wavelet, maximum values of the wavelet coefficient are obtained. Therefore, the abnormal changes in recorded signals can be successfully imaged by coefficient values of the chosen wavelet function.

The second part of the procedure was devoted to analysis of time-scale planes. For a given scalogram the value of the scale corresponding to the maximum value of wavelet coefficients was identified (Fig. 5b). Then the row of the coefficient matrix for this scale was plotted in the form of the time domain graph (Fig. 5c). The envelope of the wavelet coefficient was created by the use of the Hilbert transform [15]:

$$\hat{g}(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{g(\tau)}{t-\tau}d\tau\,, \qquad (3)$$

where $g(\tau)$ are coefficients values with respect to time. In the example shown in Fig. 5c three peaks corresponding to the reflected wave packet with relatively small amplitude values were identified. The time corresponding to damage position was determined as the interval between the incident wave and the peak with the maximum amplitude value.

Figure 6 shows continuous wavelet transform scalograms for all wave propagation signals registered at measurement points of numbers 1 to 8. The wavelet analysis was performed for scale $s = 1 \div 60$. The proposed wavelet procedure was used to determine time of reflections from damage for all scalograms.

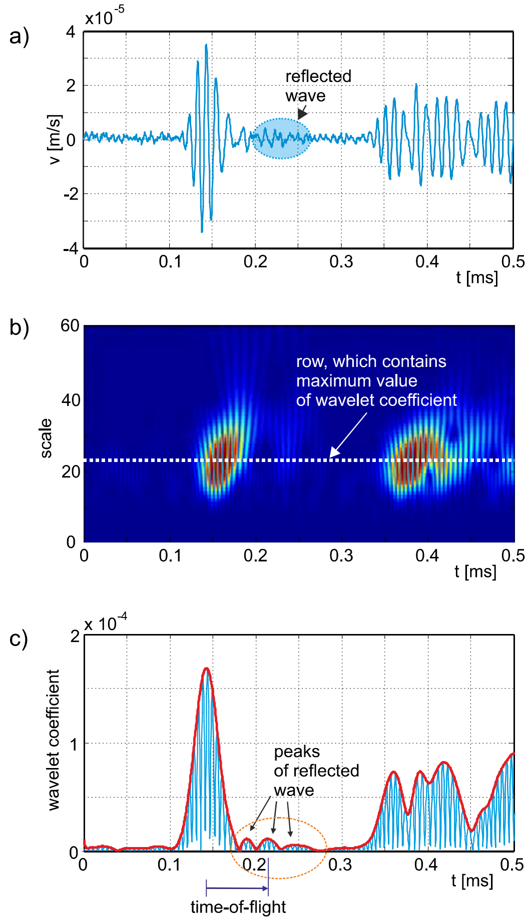

Fig. 5. The wavelet procedure of identification of reflection from damage: a) time signal of propagated Lamb wave; b) scalogram for continuous wavelet transform for scale s = 22; c) envelope of selected wavelet coefficient

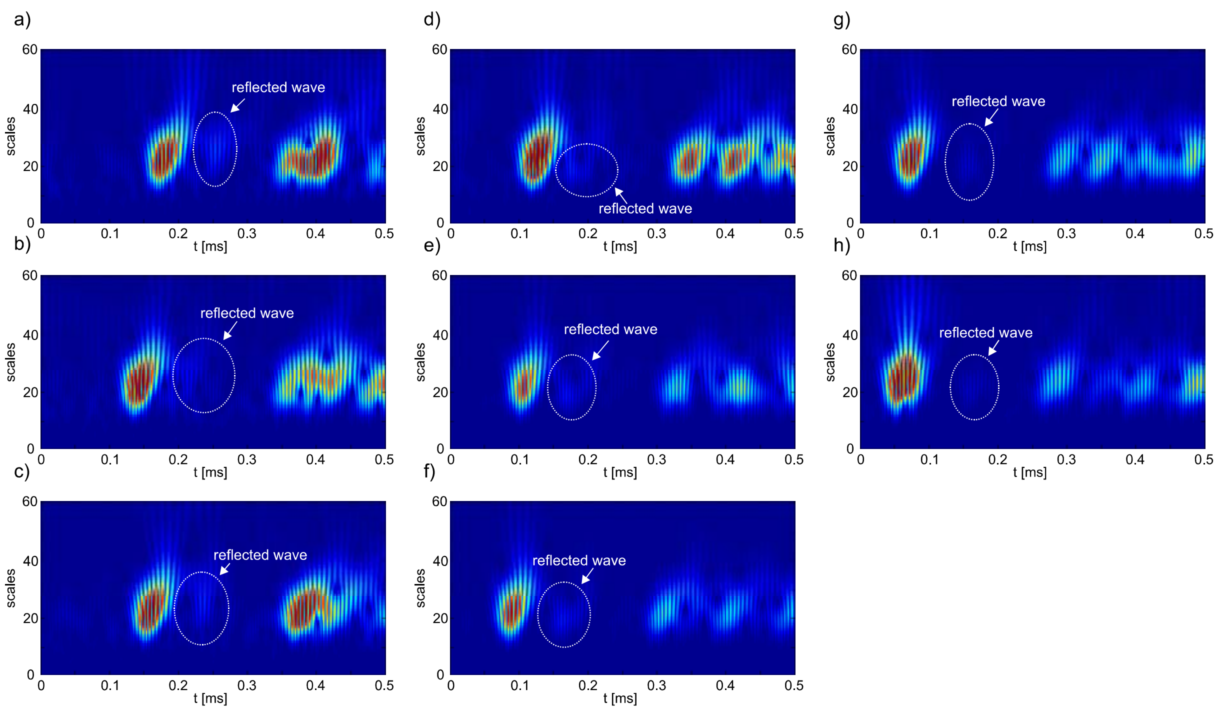

Fig. 6. Set of wavelet transforms of wave propagation time signals recorded at: a) point 8, b) point 7, c) point 6, d) point 5, e) point 4, f) point 3, g) point 2, h) point 1

4. RECONSTRUCTION OF REFLECTED WAVEFRONT

Interpretation of results must take into account the nature of the considered damage. Due to the fact that the failure has been made in the form of the notch with depth equal to half of the thickness of the plate, the part of the energy of propagating wave was reflected from the defect and the part of the energy penetrated along the plate (Fig. 7). As a result, the amplitude of the reflection from damage was characterized by a relatively low amplitude value with respect to the value of the amplitude of the excitation wave packet.

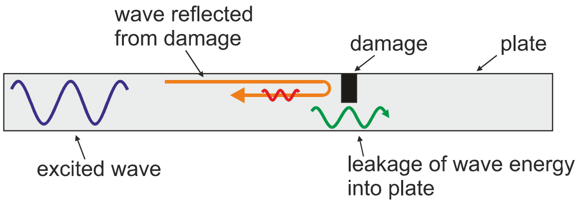

Fig. 7. Reflection of Lamb wave from damage and leakage of energy

During the experimental investigations the wave was excited by a single actuator attached to the plate at point 1. Due to the isotropy of the material with which the plate has been made, the induced wave propagated with the same speed in all directions, that means that propagation occurred from the source with the circular wavefront (Fig. 8). Because damage was made in the form of long, regular notch, the reflected wavefront also propagated circularly.

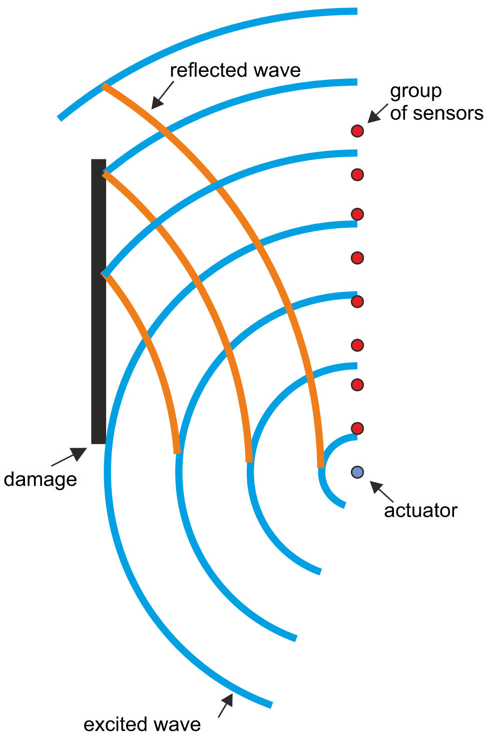

Fig. 8. Circular wavefronts in propagation of excited and reflected wave

In Fig. 9 signals registered by PZT sensors 1 to 8 are presented. The incident wave packets reaching the group of sensors were connected by the straight line. For each signal the value of time-of-flight was calculated and listed in Fig. 9. On the basis of the set of registered signals and calculated time-of-flight the shape of the reflected wavefront reaching the group of sensors has been recreated (Fig. 9) that confirmed correct identification of reflections from damage with the use of proposed wavelet procedure.

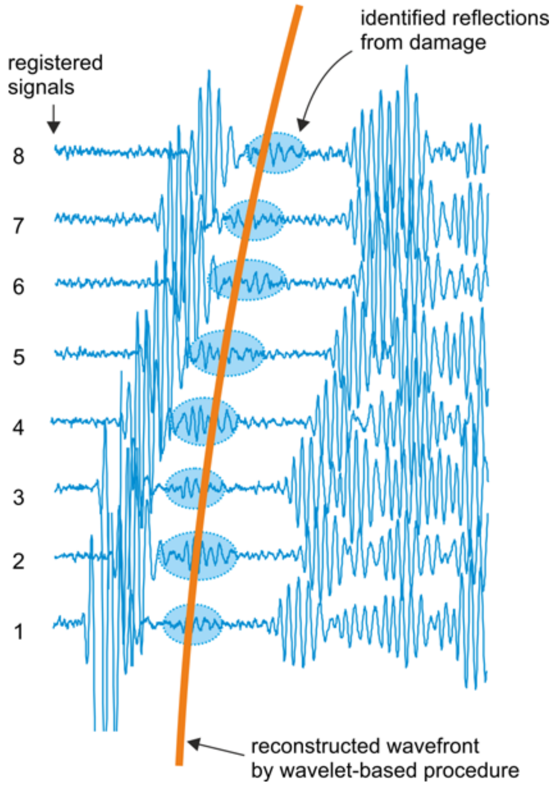

Fig. 9. Reconstructed shape of the wavefront reflected from damage by wavelet-based procedure

5. CONCLUSIONS

The paper presents the studies of guided wave propagation in the steel plate with damage. Damage detection in the examined object was based on Lamb wave signals recording at selected points and the observation of changes in the registered waveforms.

The main aim of the research was to present difficulties in the process of damage detection because of the complications which can occur during interpretation of results in the form of time domain signals. The study has indicated that even with the occurrence of severe damage and the use of modern measurement techniques enabling accurate measurement of propagating waves, the changes in signal amplitudes may be difficult to identify because of the small value of the energy of reflected waves. To overcome this problem the procedure utilizing the wavelet analysis was proposed. For precise identification of time of reflections from damage continuous wavelet transform scalograms based on the Morlet wavelet were used. Obtained results indicated that application of wavelet signal processing enabled precise reconstruction of the wavefront reflected from damage.

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