Comparison of Two Baseline-Free Damage Detection Techniques Based on Lamb Waves Propagation Phenomena

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ABSTRACT

In the article, two baseline–free damage detection and localisation methods are compared. Both are based on the signal processing acquired signals from a sensor grid located on the structure. The first algorithm uses a double element sensor grid for imaging the position of the damage. The second is based on a phased array technique, and also provides the possibility to present the analysis results in a graphical form.

INTRODUCTION

The guided waves–based damage detection and localisation methods are increasingly popular as tools for structural health monitoring. Propagating waves are very sensitive to both structure damages and boundaries. Wave interaction with damage can result in many effects, such as mode conversions or scattering. The influence of these effects on structure response signals is very often used in damage detection processes, however, in this case – on account of phenomenon complexity – a proper signal processing method has to be applied. Using baseline damage detection methods, through comparison of the reference and measured data, information about the state of the structure can be obtained. This approach has some limitations, for example, the influence of environmental conditions (temperature) [9] or the impact of operational conditions on the propagating wave. Sometimes this kind of method is inappropriate due to the impossibility of acquiring reference data. This paper focuses on baseline-free damage detection algorithms. These methods are more difficult than baseline methods but are very often the only way to perform damage identification and localisation processes. The main problem of the baseline-

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free approach is selection of the proper signal processing data technique, which allows information concerning damage to be taken from the response signal. The next difficulty is separation of the responses originating in the damage from responses from boundaries or known sources (reflection from constructional holes, edges, transducers, etc...). Detailed information about Lamb waves propagation phenomena and mathematical relationships describing wave propagation processes can be found in the literature [1,9].

TIME DOMAIN DAMAGE IMAGING

The first proposed baseline-free damage localisation algorithm is based on the time domain response analysis of the structure. The responses are acquired from the distributed actuator – sensor grid, located on the structure [3](Fig. 1b). This kind of measuring point location has an advantage over a single element grid (Fig. 1a). When actuators and sensors are placed in close proximity, the flight time of the incident wave is very short and a long part of the measured signal can be used for damage imaging (Fig. 1c).

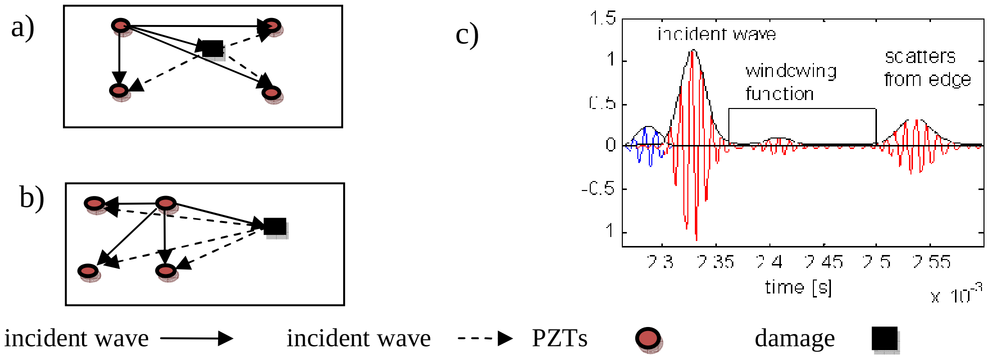

Figure 1. a) Distributed Pulse-echo grid. b) Double-element actuator-sensor grid [0], c) example of the captured signal and windowing function.

The first step in this method is estimation of the group velocity for a given plate geometry. This can be carried out in two ways: solving the dispersion equation or measuring the group velocity experimentally. The position in the time domain of the incident wave, as well as the scatters from the edges, can be estimated using the time of flight parameter[9].

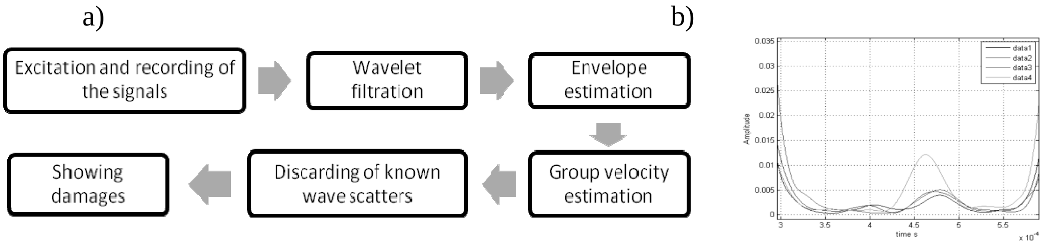

Figure. 2. a) Diagram of the damage detection and localisation method, b) processed signals

Additionally, the wavelet filtration process is performed for all signals. This allows unnecessary information to be discarded from the signal, for example, signals connected with transducer resonance which appear periodically. The damage detection process is presented in Figure 2a. The damage localisation process consists of representing an investigated area as an image, where values of the pixel $S(i,j)$ are calculated using equation [3]:

$$S(i,j) = \sum_{m}^{N} A_m f_{wg}(t_{mij}) f_m(t_{mij}), \qquad m = 1,2 \ldots, N \qquad t_{mij} = \frac{R_m^a + R_m^s}{c_g}, A_m = \frac{10}{max|f_m|} \tag{1}$$

where $S(i,j)$ – value of the given pixel, R_m^a, R_m^s is the distance from damage to the actuator and sensor respectively, f_m – envelope of the recorded signal, c_g – group velocity of the wave, f_{wg} – is the windowing function.

For each actuator–sensor path, one image can be obtained. The final result is achieved by summing the images from all paths. Generally, this technique is based on the damage imaging method presented in [3], but it was modified by using the wavelet transform, envelope extracting [8] and experimental group velocity estimation

PHASED ARRAY

The second method is based on the phased array technique. This technique creates the possibility of forming and steering the front wave generated from a set of transducers (Fig. 3.b). The beam forming is realized by delay generation during excitation of particular transducers, using equation [6].

$$t = \frac{l_x \cdot \sin(\alpha)}{c} \tag{2}$$

where l_x is the distance between transducers, c is group velocity, α is the angle between the actuator line and wave front. The acquisition process is performed with the same delay as during excitation of the structure. Due to the complexity of the phenomena appearing during the interaction between waves and the damage, some methods of signal processing have been proposed, such as wavelet filtration and envelope estimation. The diagram of the damage detection process is presented in Figure 3a. In this method the proper spacing of the transducer set is very important. Due to the aliasing effect, the maximum distance between transducers has to be determined [4,5].

Damage imaging is realized as previously using equation (1) but is performed in two steps: first when the front wave is transmitted from the left to the right, and second from the right to the left side of the plate. The direction where the amplitude of the reflected wave is highest can be suspected of damage presence. An example of the signal response of a damaged structure, processed by the proposed algorithm, is shown in Figure 2b. Detailed information about the phased array technique and beam forming can be found in the literature [7].

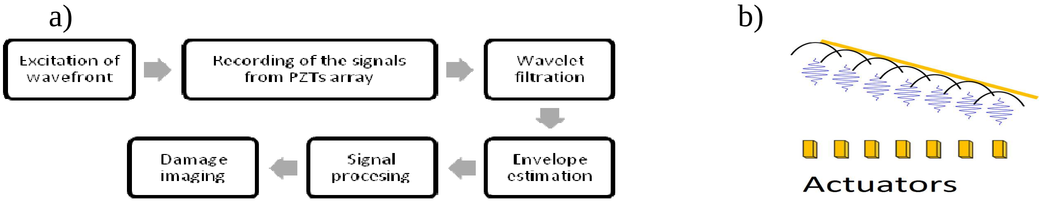

Figure. 3. a)Diagram of the phased array based damage detection method, b) beam forming

EXPERIMENTAL SETUP

To validate and compare both proposed methods, a damage detection and localisation test was performed. As an example of a damaged structure, a 2 mm thick, aluminium plate (EN AW 1050 H14) with a 10 mm long and 1 mm wide notch was used. The photo of the damage is shown in Figure 4b. The inspected plate was instrumented with Noliac CMAP07 piezoceramic transducers, with dimensions of 5x5x2 mm and with wax as an adhesive. For data acquisition and signal generation the EC Electronics PAQ 16000D system (Fig. 4c) was used. A 100 kHz Hanning windowed 5 cycle sine was generated as the excitation signal. In the first step of the test, the dispersion curves were estimated experimentally using the two-dimensional Fourier transform method [20]. The results were compared with the numerical solutions of the disperse equation. Good agreement between the numerically calculated A0 mode with the experimentally obtained dispersion characteristic is visible (Fig. 4a), but the S0 mode is hardly recognisable. Thus, A0 was chosen for the damage detection algorithms and the presence of the S0 mode was neglected. Based on the time of flight parameters and transducer spacing geometry, group velocity (equal 2.23 km/s) was estimated.

Figure 4. a) Experimental dispersion curves obtained by performing 2D FFT of measured signals and numerically calculated dispersion curves for a 2 mm aluminium plate. b) A 10 mm long, 1 mm wide notch, c) EC Electronics PAQ 16000D

COMPARISON OF THE METHOD - RESULTS

For time domain damage imaging techniques, the experiment was performed using 4 Noliac CMAP07 piezoceramic transducers, placed as in Figure 5a. The result of the algorithm is shown in Figures 5a and b. The sum of all images was filtrated using a 16x16 averaging filter. In the case of the phased array technique, the location and configuration(Fig. 6a) of the actuator – sensor grid were chosen.

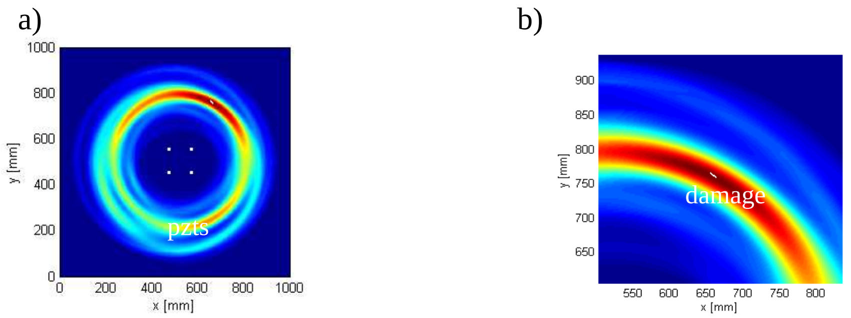

Figure 5. Damage image obtained from the experiment, most intense colour indicates damage

The time delays are realized by two synchronized PAQ-16000D devices. The results of the damage identification are shown in Figure 6b.

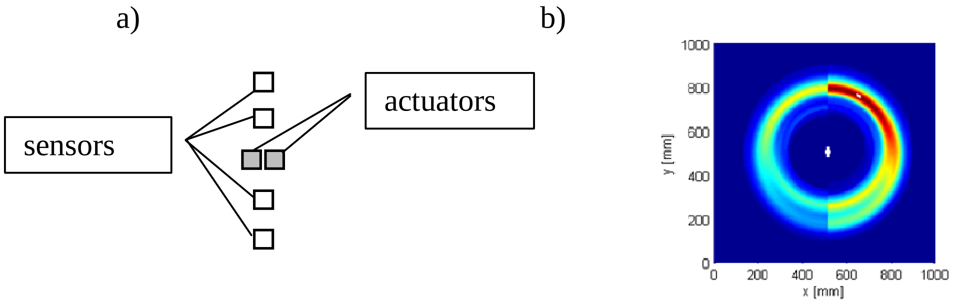

Figure 6.: a) Configuration of actuators - sensors matrix transducers ,b) Results of damage detection.

Two quantities were used to compare the presented methods: the accuracy of damage localisation and the sensitivity to damage detection. To assess the precision of localisation, the distance between the pixel with a maximum value and true damage localisation was calculated. The result of damage localisation is shown in Figure 7. The amplitudes of scattered waves vary with the direction of incidence, size and distance from the damage to the actuator and sensor. For both methods, damage localisation can be evaluated when

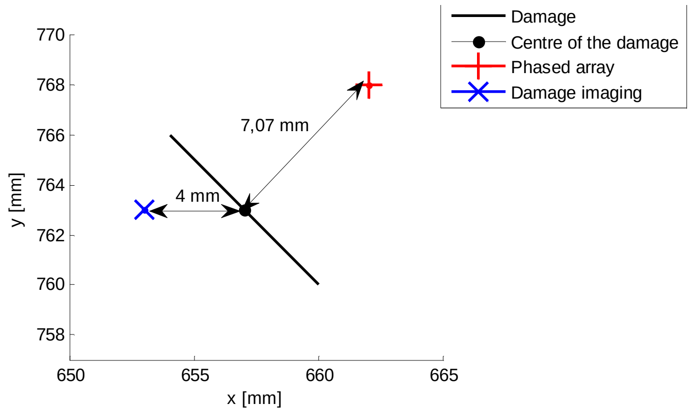

Figure 7. Real and estimated localisation of the damage.

scatter from the damage has sufficient amplitude. The sensitivity of the methods was calculated from the equation:

$$\mu = \frac{\sum_{i=1}^{n}\left(\frac{\hat{y}_n}{\max\,(y_n)}\right)}{n} \tag{3}$$

where: $\hat{y}_n$, (the maximum value of the signal amplitude reflected from the damage) is normalised by $max\ (y_n)$ - the maximum value of response from a n-the sensor. For the time domain method, the mean values of normalised scatter wave amplitudes were 0.0151 and for phased array 0.0168.

CONCLUSIONS

The phased array technique requires more advanced and complex hardware than time domain damage imaging. For time domain damage imaging only one actuator and sensor is used at the same time, so this method can perform with one generator and simple acquisition unit. The disadvantage of this approach is that some death zones occur close to boundaries and transducers. Both methods are similarly sensitive (0,0151 fir time domain method and 0,0168 for phased array), but the fact that should be considered is that excitation in the phased array technique was performed only by 2 piezo actuators. Better resolution and sensitivity is expected with an increasing number of transducers.

ACKNOWLEDGMENTS

Research funding from the Polish research project MONIT (No. POIG.01.01.02-00-013/08-00) is acknowledged by the authors

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