Structure Health Monitoring using Discrete Wavelet Transform and Piezoelectric Sensor Array

O. Saotome[1], S. V. Farias[1], E. G. O. Nóbrega[2], I. Sander[3], I. Söderquist[4] and D. S. Loubach[2]

[1]Electronics Engineering Division, Aeronautics Institute of Technology-ITA, São José dos Campos, Brazil
(Email: *osaotome@ita.br, sertone@gmail.com*)
[2]Advanced Computing, Control & Embedded Systems Lab / FEM, University of Campinas – UNICAMP, Campinas, Brazil
(Email: *egon@fem.unicamp.br, dloubach@fem.unicamp.br*)
[3]Electronics and Embedded Systems Department, KTH Royal Institute of Technology, Stockholm, Sweden
(Email: *ingo@kth.se*)
[4]HMI & Avionics Department, Saab AB, Linköping, Sweden
(Email: *ingemar.soderquist@saabgroup.com*)

INTRODUCTION

Structure Health Monitoring (SHM) allows assess structural integrity in a continuous way through developing damage detection sensors that can be permanently installed on the structure, reducing maintenance costs in aircraft structures. There are five main steps in SHM systems: damage detection, damage localization in the structure, identify the damage type, classify their severity and estimate the remaining lifetime of the structure (Souza & Nobrega, 2012). Recently, SHM methods using Lamb wave propagation has gained extensive interest. Main advantages in using Lamb wave are long distance propagation of waves that permits to scan large areas, sensitivity over various types of damages and possibility to scan structures with curved walls (Giurgiutiu, 2005).

Two common technologies suitable for embedding in structures are fiber-optic and piezoelectric sensors. The piezoelectric sensing systems are cheaper than the systems based on fiber-optic sensors (Kudela, et al., 2007).

Usually three configurations are used in damage localization: pitch-catch, pulse-echo and phased array (Li, et al., 2014). In the first case, damage is detected by elastic wave that propagate through the damage. Souza et al. (2012) presented a circular array of PZT-piezoelectric sensors and a central PZT-piezoelectric actuator. The damage was detected using a pitch-catch configuration. In pulse-echo case the damage detection and localization is usually made by measuring the time of flight (TOF) of the reflected signal (Giurgiutiu, 2005). Phased Array consists of a group of transducers in which the elements are excited with particular time delays, performing a virtual scan using beamforming in order to detect damages. Yu et al. (2005) presented a linear phased array of PZT-piezoelectric transducers with advanced signal processing techniques to improve damage detection. The signals acquired by the sensors were filtered using Wavelet transform in order to improve the Hilbert transform response. Souza et al. (2012) used a Shannon entropy criterion to choose the best Wavelet-mother in order to filter the PZT-piezoelectric signals, and this work was focused in detecting damages in beams.

This paper proposes the extension of the work presented by Souza et al. (2012) in order to detect damages in a plate. The phased array of PZT-piezoelectric sensors is used to scan the whole plate through spatial-temporal filter tuned for pre-defined directions. The discrete wavelet transform (DWT) filters each signal acquired and the Shannon entropy criterion is applied to choose the best mother Wavelet. Finally, the envelope signal for each direction is obtained using Hilbert Transform. The damages are detected and localized through the image obtained by correlation of the signals. The proposed SHM method was tested by using MATLAB simulations. The method was capable to locate damages in range and azimuth coordinates in a simulated metal plate and has potential to be used in real aircraft structures.

LINEAR PHASED ARRAY FOR DAMAGE DETECTION

A linear phased array of piezoelectric transducers is depicted in Fig. 1. The array consists of 10 elements, m = 1, 2, …, 10, spaced at equal distance *d*. The signal is emitted by the transducer number 1, reflected by a damage in the direction θ and received by all transducers. Considering that the damage is far from the array, then the far-field parallel-ray approximation can be applied (Giurgiutiu, 2005) .

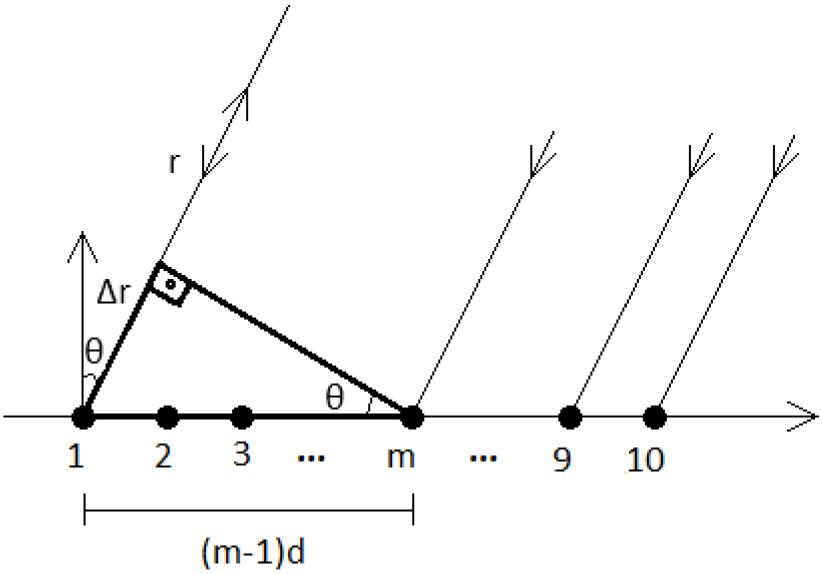

Fig. 1 - Linear Phased Array

The signal emitted $S_T(t)$ by the transducer 1 is given by the Eq. (1).

$$S_T(t) = S_W(t)\cos(2\pi f_c t) \tag{1}$$

where $S_W(t)$ is a finite-duration Gaussian window and f_c is the frequency of the carrier signal. The signal received by each transducer is given by the Eqs. (2) to (4) (Giurgiutiu, 2005).

$$S_m(t,\theta) = \frac{1}{r} S_T\big(t - \tau + \Delta\tau(m,\theta)\big) \tag{2}$$

$$\tau = \frac{2r}{c} \tag{3}$$

$$\Delta\tau(m,\theta) = \frac{d(m-1)\sin(\theta)}{c} \tag{4}$$

where:

r is the damage distance from array;
θ is the damage direction;
d is the distance between the transducers;
c is the wave speed.

Eqs. (2) to (4) indicate that it is possible to find the damage position through time delay measurement, which is related to the parameters r and θ. Therefore, adding a controlled delay factor to the Eq. (2) and, after that, summing all the signals $S_m(t,\theta)$ results in the Eqs. (5) and (6).

$$S(t,\theta) = \frac{1}{r}\sum_{m=1}^{10} S_T\big(t - \tau + \Delta\tau(m,\theta) - \delta(m,\theta_s)\big) \tag{5}$$

$$\delta(m,\theta_s) = \frac{d(m-1)\sin(\theta_s)}{c} \tag{6}$$

where $\delta(m,\theta_s)$ is the controlled delay factor for each transducer.
The damage distance r is calculated by the time-of-flight (TOF) that is given by the parameter τ, whilst the damage direction θ is calculated through scan process by calculating $\delta(m,\theta_s)$ for each direction θ_s and the determining maximum value.

DENOISING BY DISCRETE WAVELET TRANSFORM

Wavelet transform is a tool used to represent signals in time-scale domain. Generally, the scale is related to the signal frequency. In comparison with the Fourier transform, the Wavelet transform is more appropriate to analyze non-stationary signals (Mallat, 1998).
The continuous Wavelet transform (CWT), Eq. (7), of a signal $x(t)$ at scale s and time position u is computed by correlating $x(t)$ with a Wavelet atom (Rucka & Wilde, 2006).

$$CWT(u,s) = \int_{-\infty}^{+\infty} x(t)\frac{1}{\sqrt{s}}\psi^*\left(\frac{t-u}{s}\right)dt \tag{7}$$

where $\psi(t)$ is called mother Wavelet.
In a CWT the time displacement u and scale s accept continuous values, however in a discrete Wavelet transform (DWT) they assume a discrete range of values. The DWT is presented in the Eq. (8).

$$DWT(n,j) = \int_{-\infty}^{+\infty} x(t)\frac{1}{\sqrt{2^j}}\psi^*\left(\frac{t-n2^j}{2^j}\right)dt \tag{8}$$

where $(.)^*$ denotes complex conjugate, n=1,2,…,N and j=1,2,…,J with $N=2^J$.
Therefore, the signal $x(t)$ is decomposed over a orthogonal basis $\Psi_{n,j}(t)$ according to the Eqs. (9) and (10) (Mallat, 1998).

$$x(t) = \sum_j \sum_n DWT(n,j)\Psi_{n,j}(t) \tag{9}$$

$$\Psi_{n,j}(t) = \frac{1}{\sqrt{2^j}}\psi\left(\frac{t-n2^j}{2^j}\right) \tag{10}$$

The output of each level of the decomposition process presents an output signal called detail d_j , that is described by Eq. (11).

$$d_j(t) = \sum_n DWT(n,j)\Psi_{n,j}(t) \tag{11}$$

The mother Wavelet should be orthogonal and some common options are *Haar*, *Daubechies* and Coiflet.
Generally, mother Wavelet is chosen by their similarity to the signal components. The degree of similarity between the Wavelet mother and the signal can be measured through Shannon entropy (Li, et al., 2009). The Shannon entropy of detail level d_j is given by the Eqs. (12) and (13).

$$S(d_j) = \sum_n \frac{DWT(n,j)^2}{R} ln\left(\frac{DWT(n,j)^2}{R}\right) \tag{12}$$

$$R = \sum_j \sum_n DWT(n,j)^2 \tag{13}$$

The Shannon entropy measures the randomness of a process. The mother Wavelet with lowest Shannon entropy has the highest similarity with the signal (Li, et al., 2009).
The Shannon entropy can be used to increase the signal-to-noise of the signal by reconstructing the signal using the detail level with the lowest entropy value (Souza & Nobrega, 2012).

RESULTS

The proposed method for damage detection was validated by using MATLAB simulation of the Lamb wave propagation through an aluminum plate (Fig. 2). The simulated plate has 2 m width, 2 m height and 5 mm thickness. The array with 10 piezoelectric transducers was positioned in the center of the plate, the array is represented by a yellow line in the figure 2. The distance between the transducers is 2 cm.

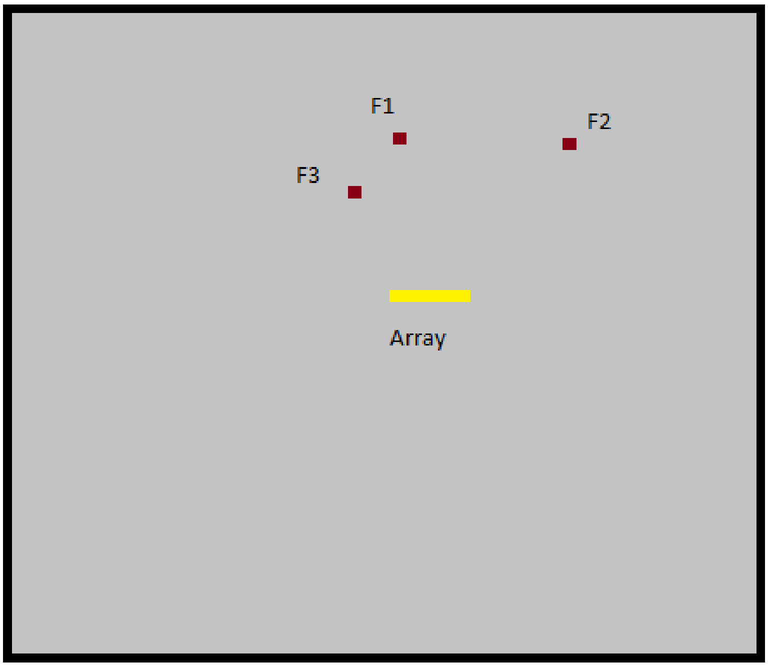

Fig. 2 – Aluminum plate with damages

Three damages F1 (0.6 m, 0°), F2 (0.7 m, 40°) and F3 (0.4 m, -10°) were simulated.
The signal was emitted with a carrier frequency of 100 kHz, the wave propagates with phase velocity of 5000 m/s and 9 dB signal-to-noise ratio. The signals received by the transducers 1

and 10 are depicted in Fig. 3. The emitted signal is indicated by the letter T and the reflections from the damages are indicated by the letters F1, F2 and F3.

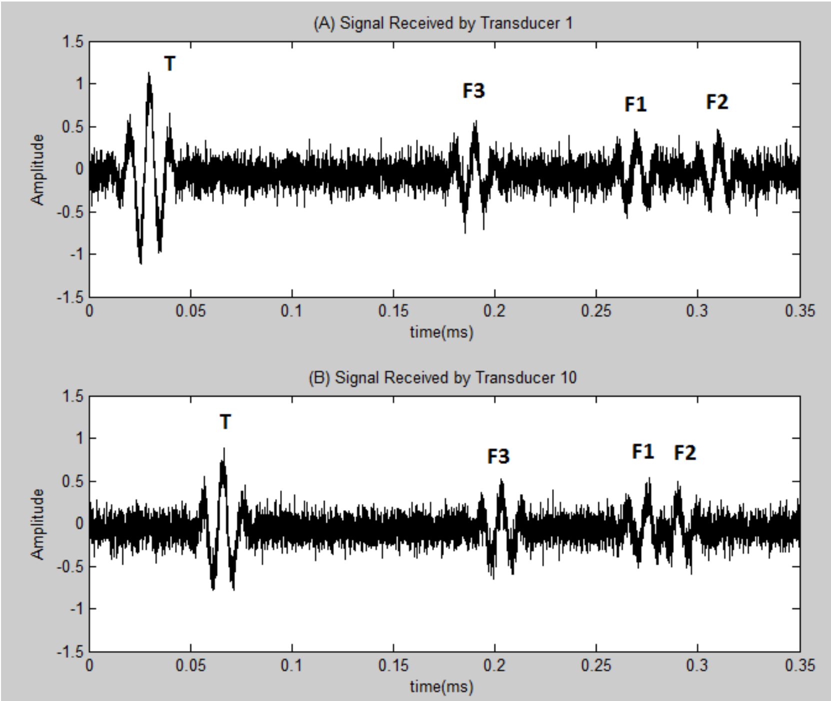

Fig. 3 – Received Signals

The signals received by each transducer should be filtered through the DWT. There was chosen three mother Wavelets, which shapes are similar to the emitted signal (*Daubechies 10, Biorthogonal 4.4 and Symlets 10*). The Shannon entropy calculation (Eq. 12) for each mother Wavelet and the signal received by the transducer 1 is shown in Fig. 4.

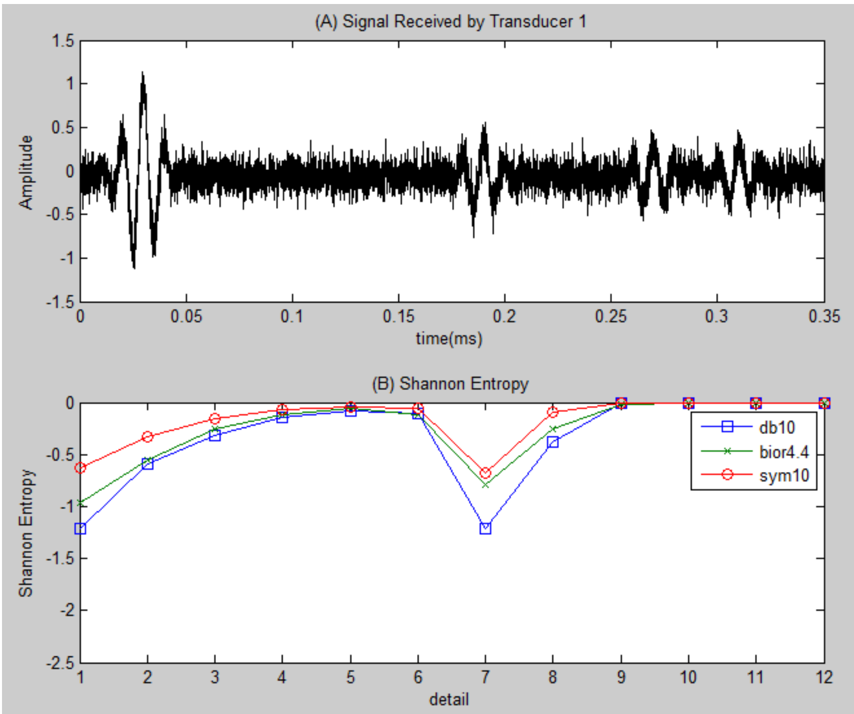

Fig. 4 – Shannon Entropy Results

The lowest value of entropy was obtained for mother Wavelet Daubechies 10 (db10) to the detail level 7. The signal filtered using the level 7 detail is showed in the Fig. 5.

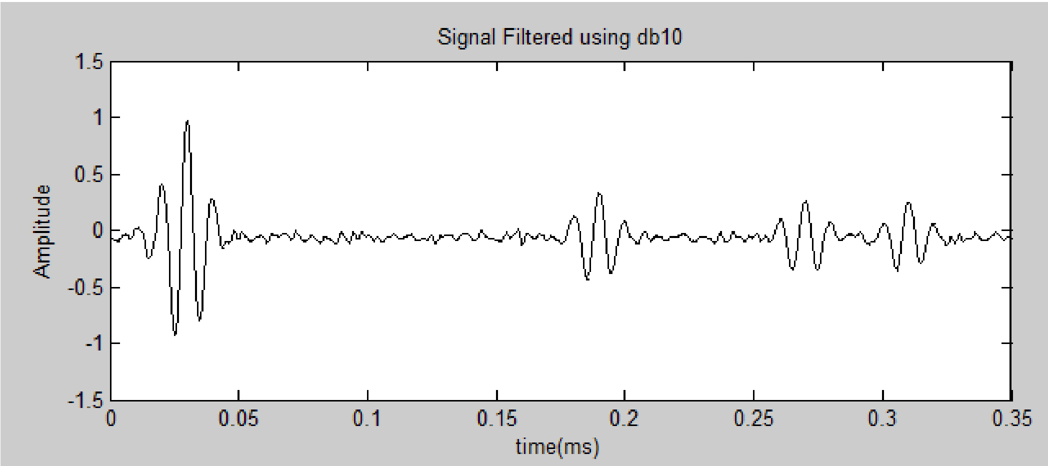

Fig. 5 – Signal received by transducer 1 and filtered using db10

The signal *S(t, θ)* (Eq. 5) is calculated for $\theta \in (-90^o, 90^o)$, then the Hilbert Transform is calculated (Yu & Giurgiutiu, 2005). The phased array response image, depicted in Fig. 6(B), is constructed using the signals *S(t, θ)*. In Fig. 6(A), the phased array image is calculated without the DWT filter. In Fig 6(B) the damages are more clearly identified in comparison with Fig. 6(A).

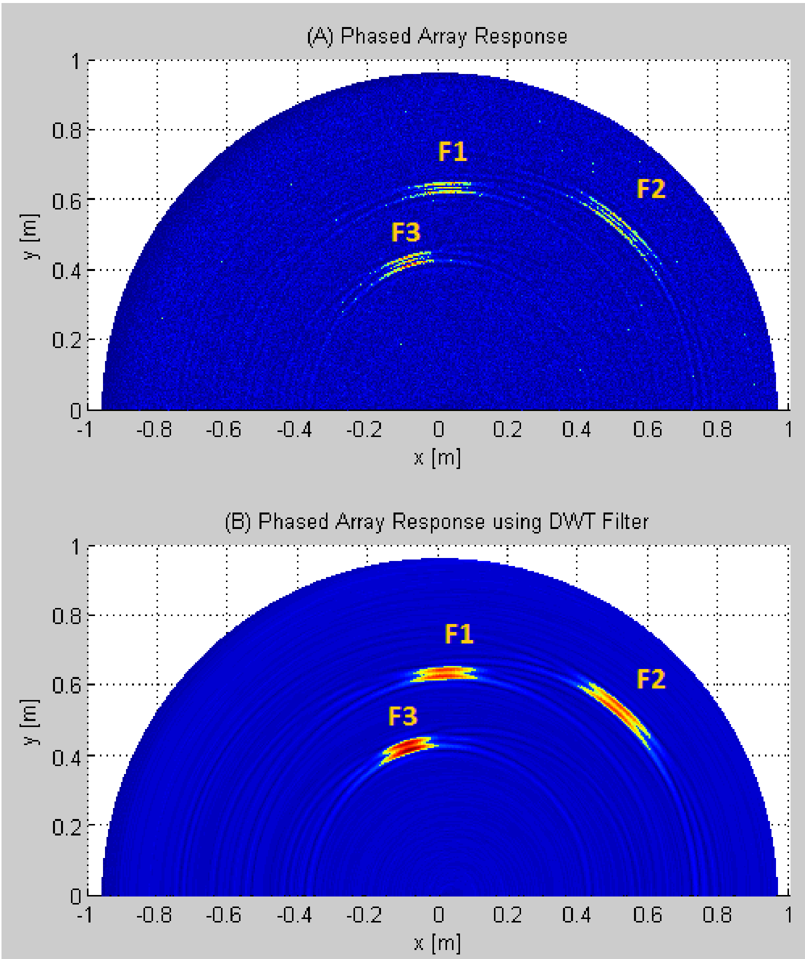

Fig. 6 – Phased Array Image

CONCLUSIONS

This work presented a method to detect and localize damages in plates. The damages are detected by the reflections of Lamb waves from them. The method uses the DWT and Shannon entropy to increase the signal-to-noise ratio.

The method was validated through simulation results. Three damages were detected on an aluminum plate using phased array with ten transducers.

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