Application of the Beam-Forming Technique for Damage Detection in Plate Like Structures

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ABSTRACT

Guided waves can travel over a long distance, they are highly sensitive to any discontinuity they might encounter along their propagation path, and they can be generated and sensed by piezo electric transducers easily bonded to the external surface of the structure under investigation.

When guided waves are generated and sensed by an array of phased sensors, it's possible to steer the wave-front in a specific direction (beamforming technique, widely used in electromagnetic radar applications). The improvements respect to the omnidirectional reception/transmission is known as receive and transmit gain, respectively.

In this work a linear array of sensors is used to generate an ultrasonic wavefront steered in a specific direction, like structural radar. This effect is achieved by the combination of constructive and destructive interference of signals generated by the linear array of sensors, sequentially fired with appropriate time shifts. Numerical simulations are carried out with the LS-DYNA, an explicit Finite Element (FE) code, on an aluminum panel 6061-T6 (0.7m × 0.8m × 1mm). The damage to be identified is a 5mm diameter hole with 20mm edge cracks, located at a distance of 250 mm away from the center of the array along a direction at 60°. The array of sensors consists of 9 disk-shaped piezo patches (10mm in diameter and 0.2 mm in thickness) with a pitch of 12mm. A five-cycles sine signal with 225 kHz center frequency and in a Hanning window is used as the excitation for each element of the array with an appropriate time delay to direct the main lobe along the desired direction. A very clear reflection of the S_0 waves is produced from the crack edges. From the echo reflected and returning on the array, it's possible to evaluate the time of flight of the signal (TOF) from which the distance of the damage from the sensors array can be determined, and the angular position of the crack by evaluating the time shift of the signal received by each sensor in the array.

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The experimental tests are carried out in a 1m x 1m x1 mm aluminum panel with the same sensor array and edge cracked hole used in the simulation. The sources in the array are sequentially fired using the round-robin technique. A number of receivers located along the panel edges have been also used to detect the damage direction in pitch-catch mode.

INTRODUCTION

Modern maintenance scenarios, where the inspection of the structure is carried out only when needed, are a topic on which airlines, aircraft manufacturers and scientific community have been spending big effort during the last two decades. There is a large inventory of aircraft structures in operation throughout Europe and the world that are undergoing continuous degradation through aging. Moreover, this number is increasing by around 5% every year, resulting in significant negative impact on the economy of many nations. The degradation of critical structural components is controlled through careful and expensive regularly scheduled inspections in an effort to reduce their risk of failure. An SHM system able to interrogate a structural sub-component with accuracy and reliability of a traditional NDT technique would allow to substitute the actual two-level inspection approach, based on visual inspection followed eventually by NDT analysis, with a single-level inspection highly automated based on sensors that are permanently and not invasively installed on the structure to monitor. The ultrasonic research community has studied guided waves for nondestructive evaluation of plate-like structures for several decades [1,2]. Guided waves are created by the constructive interference of the bulk waves reflected between the surfaces of the plate; these waves have a number of characteristics that are different from those of the bulk waves. First, they are, in general, multimodal and dispersive; the particle motion (symmetric or extensional and antisymmetric or flexural) and the velocity of each mode depends upon the thickness and material properties of the plate, as well as the frequency of the excitation of the wave. Second, they can propagate a much larger distance than the bulk waves without significant decay in their amplitude. Third, and most important, they are extremely sensitive to the presence of discontinuities in their path, and carry information on certain properties of the flaws as they propagate away from the flaws. Finally, it is relatively easy to generate and record the guided waves using (PZT) actuators and sensors that require very little power, and are therefore suitable for online structural health monitoring [3-5].

THE BEAMFORMING TECHNIQUE

The beam-forming is a widely used technique of signal processing to transmit or receive directional signals with arrays of sensors. In this work a linear array of sensors is used to generate an ultrasonic wave-front steered in a specific direction. This effect is achieved by the combination of disruptive and constructive interference of signals generated by the linear array of sensors sequentially fired with a proper phase shift.

The advantage of using a beam-forming instead of an omnidirectional transmitter or receiver, is the spatial selectivity and the gain increase due to concentration of most of the energy in a narrower propagating lobe.

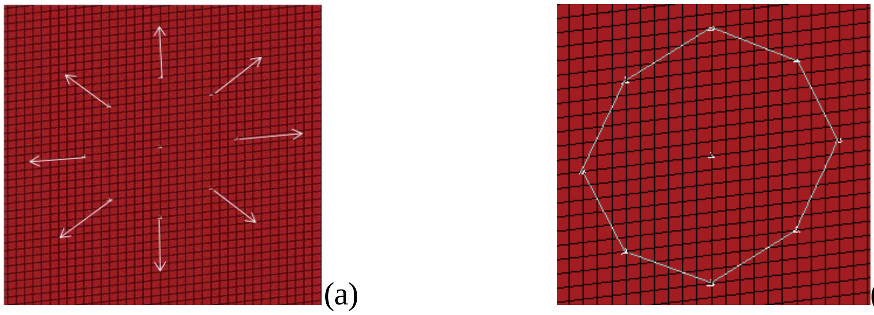
The beamforming is obtained by assigning a time delay to each individual piezo. The delay required to achieve a desired angle of steering φ_0 can be easily calculated by the following relation:

$$\Delta_m = m\frac{d}{c}\cos(\varphi_0)$$

where $m=0 \ldots n-1$, n is the number of the piezos of the array, d is the distance between each piezo, c is the group velocity of the Lamb waves. In order to take advantage of the constructive and destructive interference, it is appropriate that the distance d is about half the wavelength λ of the signal generated, with $\lambda = c / Fc$ and Fc the carrier frequency of the signal generated. Moreover, to calculate the distance of the damage from the array the simple relationship $c = 2 * S / T$ is used, where S the distance covered by wave from the sensor array to the damage and back to the sensor array, T is the time of flight of the signal.

NUMERICAL SIMULATIONS

Numerical simulations are carried out on an aluminum panel 6061-T6 (700mm × 800mm × 1mm). The damage to be identified is a 5mm diameter rivet hole with 20mm edge cracks, located at a distance of 250 mm away from the center of the array along a direction at 60°. The array of sensors consists of 9 disk-shaped piezo patches (10mm in diameter and 0.2 mm in thickness) with a pitch of 12mm. Preliminary analyses are carried out with a commercial explicit finite element code, LS-DYNA. In Figure 1 it is shown the modeling approach for piezos. The transmitting piezo patches are modeled with 8 in-plane forces directed radially from piezo center, while the voltage provided from the receiving piezos is evaluated through the variation of area included into the octagon delimited by the 8 nodes, since the voltage is related to the area variation by a piezoelectric electromechanical coupling constants.



(a) (b)

Figure 1 - Piezo modeling: (a) actuator; (b) sensor.

Piezos are excited by a 4,5 sine Hanning windowed signal, with a frequency of 300 KHz, as shown in Figure 2. In Figure 3 some results of steering tests and interaction of S_0 wave with the hole with edge crack are reported. It is interesting to note that the FE analysis is able to reproduce the mode conversion during the scattering from a crack. Although the beam width increases with angle, due to its directionality a very clear reflection of the S_0 waves is produced from the crack edges.

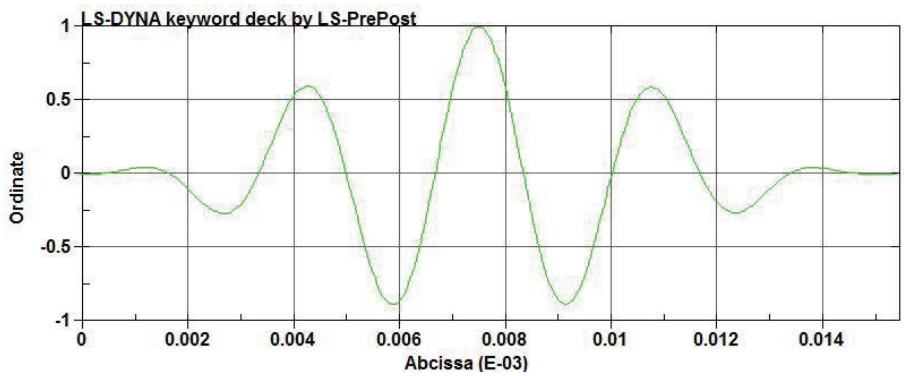


Figure 2 – Piezos exciting signal

These reflected waves can be recorded by the sensors array itself in a pulse-echo mode to evaluate the time of flight (TOF) from which the distance of the damage from the sensors array can be determined. In principle the analysis of these signals may also provide the angular position of the back-reflecting source, by evaluating the time shift of the signal received by each sensor in the array. However, the signals recorded by other sensors distributed over the structure in a pitch-catch mode give more precise information about the angle between the sensors array and the damage. This is demonstrated in the experimental tests reported in the next section.

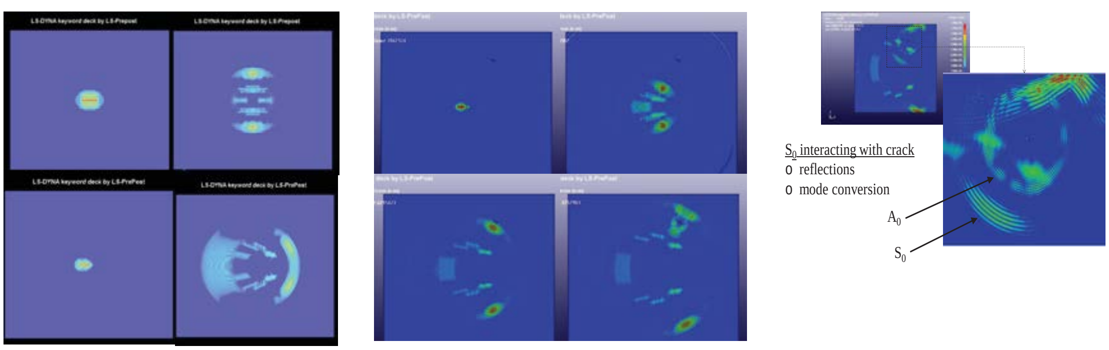


Figure 3 - FE simulations: 90° and 30° steering tests (left), scattering of a 60° ultrasonic beam from an hole with edge cracks (center), a detail of the mode conversion of an incident S0 beam due to the scattering

EXPERIMENTAL SETUP

An aluminum panel 6061-T6 (1m×1mx1mm) with a rivet hole with cracked edges 20 mm wide has been used for the experimental test. The array of sensors consists of 9 disk shaped piezo patches (the same as described in the previous section) with a pitch of 12mm. Figure 4 shows the detail of the sensors array. Three piezo patches, acting as receivers, are bonded on the panel at 90°, 60° and 30° degrees with respect of center of the array, at a distance of 250 mm (see Figures 4 and 5). Preliminary tests are carried out on the intact aluminum panel, using a five-sine cycles signal in a Hanning window as excitation with a center frequency of 225KHz. The frequency is reduced respect to the numerical simulations due to a reduced pitch among the piezo disks respect FE model.

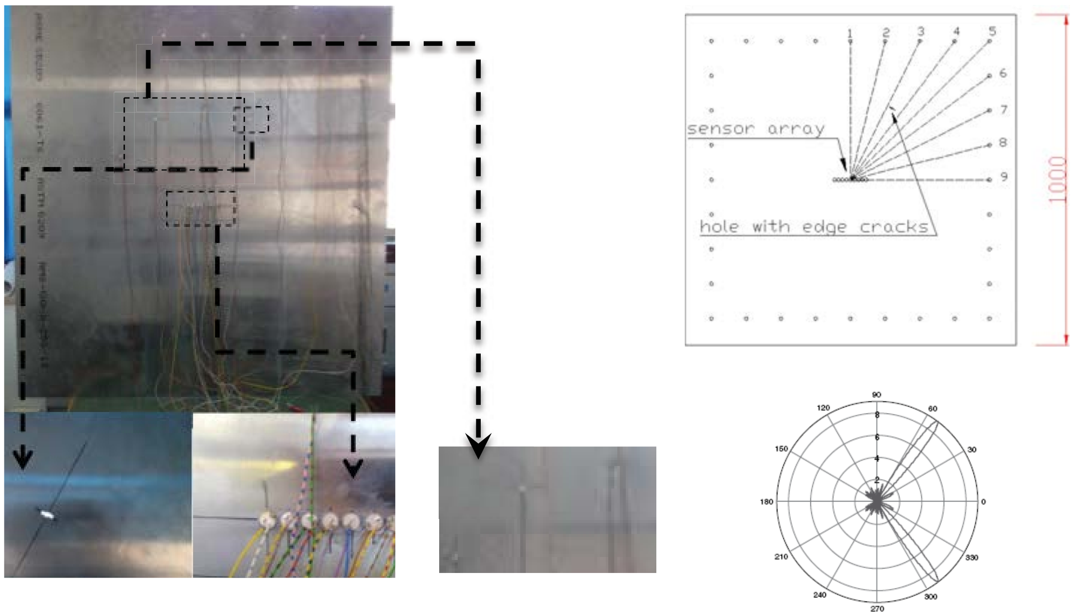


Figure 4 – The experimental set-up for defects detection in an aluminum panel. A detail of the sensor array and rivet hole is showed in the left picture on the bottom side. Three piezo patches used as receivers (R1, R2 and R3, see also figure 5) are showed in the center picture. The convention for the steering is showed

The multiple phased firing of each sensor of the array is performed using the Round-Robin technique [3], taking advantage of the superposition principle to avoid experimental complexities of the hardware. Three steering tests are performed to obtain a propagating waves beam at 90°, 60° and 30° intercepted by the receivers R1, R2 and R3. In Figure 5 the gain variation of the phased array transmitter with the propagation direction is shown. The gain is defined as the ratio between the signal energy propagating in these directions compared to the signal energy that would be propagated if the antenna were not directional. From Figure 5, the high level of directionality is showed. Each receiving sensor (R1, R2 and R3) measures a high signal level only when the array of sensors transmits in the direction of the receiver itself. Moreover, when the beam direction is steered from 90° (normal to the sensors array) to 30° the energy collected by all the receivers decreases as the beam-width increases.

A hole with edge cracks is then drilled in the aluminum panel and propagation tests are carried out to estimate the capability of the system to detect the damage. A number of receivers located along the panel edges are used to detect the damage direction, as showed in Figure 4 (left). When the wave beam encounters the cracked hole and is reflected back as in the simulation of Figure 3, the signal strength decreases beyond the discontinuity. Figure 6 refers to a test performed with the beam directed toward the receiver #3 (see also Figure 4). It can be noted that the maximum signal strength is sensed by the receiver #3 due to beam directionality. Furthermore, the receivers #3 and #4 sense the maximum decrease of signal strength, due to the presence of the crack. This occurrence allows locating on which direction the damage is located, while the time of flight measurement allows to determine the distance from the center of the array.

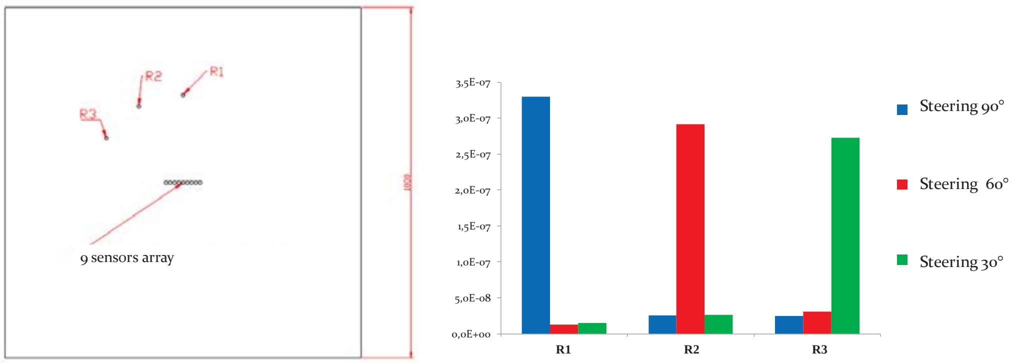


Figure 5 - Experimental evaluation of the beam directionality and gain dependence from the beam direction

Finally, since the sources in the array are, beam forming using experimental device complexities are avoided.

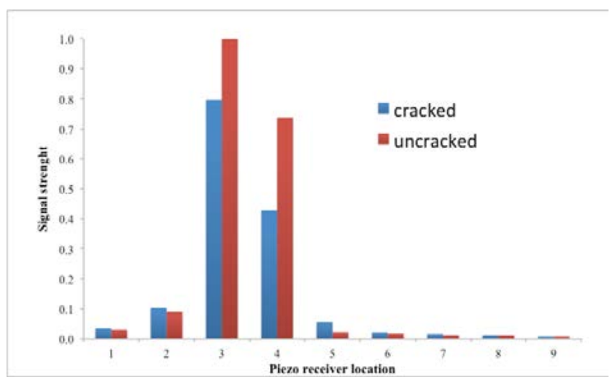


Figure 6 - Experimental evaluation of strength of the signal received by the edge receivers with and without damage.

CONCLUDING REMARKS

It is proved that ultrasonic waves propagation based on the beam forming technique is a very promising approach for structural health monitoring purposes. Using both numerical simulations and experimental tests it is shown that higher precision in damage detection is achieved if both pitch-catch and pulse-echo techniques are used.

The advantage of using the beam-forming instead of an omnidirectional transmitter or receiver is the spatial selectivity and the gain increase due to concentration of most of the energy in a narrower propagating lobe. The signal analysis for damage detection is then simplified respect to an omnidirectional wave propagation, as reflections from discontinuities located on the propagation paths different from the steered direction are drastically reduced. On the other hand it should be taken account of the fact that the beam width (i.e. the width of the lobe) increases with the steering angle, even though for steering angles within +/- 45° it can be neglected. The work has been carried out on metallic plates. For composite plates that are not transversely isotropic in the plane of the plate the beam width depends also on the steering direction. Numerical simulations and tests are currently in progress for orthotropic plates in order to evaluate the efficiency of the beamforming technique for composite materials.

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