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# A novel self-tuning method for Lamb wave inspection of plate-like structures

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**Abstract**
A novel self-tuning technique for Lamb wave inspection especially appropriate for anisotropic materials such as some composites is presented. Propagation speeds for the different Lamb modes are in-situ tuned for the different directions, covering the whole azimuth range. By performing a frequency sweep, optimal frequencies for working with each wave mode are also selected. The proposed method is firstly evaluated by multiphysics numerical tests. Finally, the method is applied for locating a defect in a Fiber Reinforced Composite plate by reflection tomography.

**Keywords:** Lamb waves, anisotropic material, Piezoelectric wafer active sensors, structural health monitoring, PWAS, SHM, PWAS phased array

## 1. INTRODUCTION

According to [1], the 27% of an aircraft life cycle is spent on inspections and repairs. Aeronautical industry demands novel inspections technique in order to save costs without cutting down the inspection quality.
Lamb waves are elastic waves that propagate in solid plates [2]. Different methods have been proposed for Lamb wave based thin-walled aeronautic structure inspection. Lamb Waves are dispersive, with multiple modes, each of them propagating with different frequency dependent velocities [3, 4]. Piezoelectric Wafer Active Sensors (PWAS) phased arrays bonded to plate structures are usually employed in order to generate and detect Lamb waves [5, 6, 7, 8]. Different PWAS phased array topologies have been proposed for isotropic plates [9]. Usually, PWAS are arranged as uniform linear arrays (ULAs), where each element plays the role of both transmitter and receiver. It is well known that ULAs generate grating lobes, complicating Lamb wave inspection. In order to avoid grating lobes, different 2D array topologies have been proposed in the literature [10, 11, 12]. These techniques have also been applied for anisotropic materials, such as composite thin-walled structures [13, 14], taking into account different velocities depending on the propagating direction. Nevertheless, direction dependent Lamb wave velocities must be known in order to apply these methods.
PWASs bonded to the surface are strain-coupled with inspected structure. Therefore, PWAS transducers couple to the structure through the bonding adhesive. The transfer of energy between a PWAS and the structure is optimized at certain frequencies that depend on the structure geometry and properties, as well as the bonding adhesive, the PWAS properties and the Lamb wave mode [15].

In this paper, an adaptive tuning method is proposed for selecting optimal inspection frequencies that maximize energy transfer between PWASs and structure for a specific Lamb mode. Plate inspection is executed at the optimal frequencies, where a particular Lamb wave mode is maximized in relation to other modes. The method also determines propagation velocities as a function of the propagation direction. These velocities serve to adjust the Direction of Arrival (DoA) algorithm, as a previous step for obtaining a reflection tomography of the inspected plate.

The rest of the paper is organized as follows. The adaptive self-tuning method to select the optimal inspection frequencies is introduced in Section 2. In section 3, the optimal frequency selection method is tested by comparing numerical simulations and analytical models from the literature. In section 4, the proposed method is applied to locate a hole in an aluminum plate by means of B-Scan image. In section 5, the method is experimentally evaluated by inspecting a defective aeronautically graded Carbon Fiber Reinforced Polymer (CFRP) plate. Finally, conclusions are presented in Section 5.

## 2. ADAPTIVE SELF-TUNING METHOD

The proposed self-tuning method is based on a Single Transmitter Multi Receiver (STMR) annular topology, where a set of n PWAS receiver discs are arranged into a ring and a single PWAS transmitter disc is located at the center of the ring, as shown in figure 1 (left). The transmitter is excited by n periods of a sinusoidal signal windowed by a Hanning window. The frequency of the sinusoidal signal is swept over a range of frequencies of interest. These pulses excite the inspected plate, the transmitter PWAS acting as point source and radiating Lamb waves in an omnidirectionally (see figure 1).

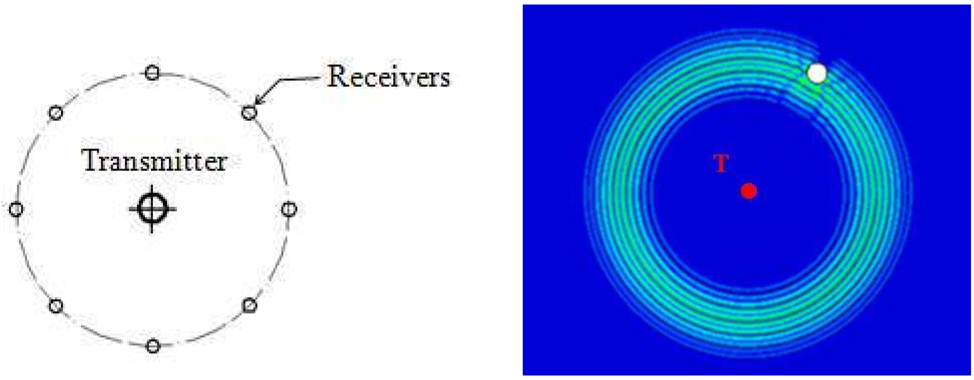


Figure 1: STMR ring topology (left) and wave front radiated by the transmitter PWAS (right)

The omnidirectional circular wave front generated by the transmitter is detected by each of the n receivers. As the radial distance from the transmitter to the receivers is known, the velocity and attenuation of each Lamb mode can be obtained. The time that takes for each mode to arrive to the transmitter is determined by the peaks of the cross correlation between the transmitted signal and the measured signal in each of the receivers, as shown in figure 2. This procedure allows both determining the frequency that maximizes the transmitted energy, as well as the velocity and attenuation for each Lamb mode in each direction. The method is especially applicable to varying conditions, such as temperature, or materials with unknown or uncertain properties Moreover, for anisotropic materials, different velocities and attenuations are obtained for each direction before inspection, and employed for tuning the DoA algorithm [13, 14] as a previous step for the reflection tomography imaging algorithm [16, 17, 18].

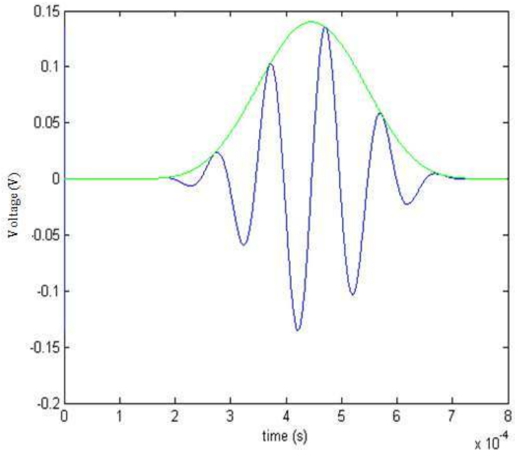


Figure 2: Detection of arrival by correlation

## 3. OPTIMAL INSPECTION FREQUENCY SELECTION

This section presents numerical and simulation results obtained by the Finite Element Method (FEM) with Abaqus. The aim of the numerical experiments is to evaluate the capabilities of the proposed self-tuning method to determine optimal excitation frequencies. An isotropic material is considered in order to compare simulation results with closed-form expressions obtained from analytical models. The structure is a 2 mm-thick 6082-T6 aluminum alloy plate, with 700x700 mm size. The plate has a 15 mm radius hole located at a distance of 150 mm and an angle φ=60º from its center (see figure 3). Mechanical properties for the aluminum are presented in Table 1. The plate is excited with a 3.5-mm radius PWAS disc placed on its center. A circular array of 8 receivers is considered. Ideal bonding is assumed between the PWAS and the structure and the excitation is transferred at the ends of the PWAS [15].

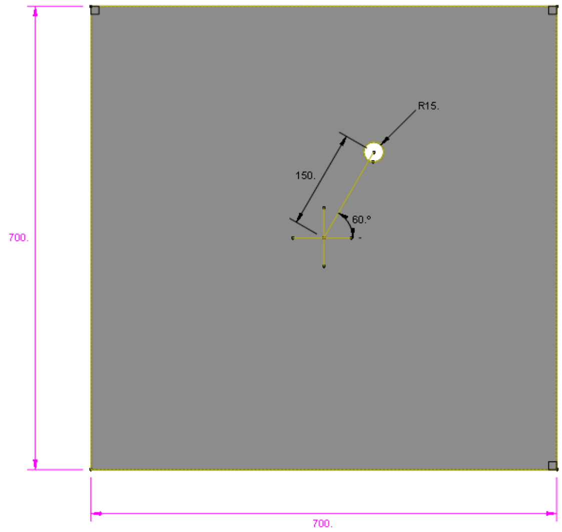


Figure 3: Plate dimensions

| | |
|---|---|
| Young’s modulus, E (GPa) | 70 |
| Shear modulus, G (GPa) | 25 |
| Poisson’s modulus, υ | 0,33 |
| Density, ρ (kg/m3) | 2700 |
| Young’s modulus, E (GPa) | 70 |

Table 1. Mechanical properties for the Aluminum 6082-T6.

The optimal excitation frequency for maximizing the energy transfer for a particular Lamb wave mode has been obtained by analytical models from the literature [6, 7, 8, 15]. Radial displacement amplitude vs. frequency has been calculated for both A0 and S0 Lamb wave modes, assuming a harmonic shear-stress boundary excitation applied to the upper surface of the plate.

In the FEM simulations, the plate is meshed with 8-node linear bricks with reduced integration, C3D8R. To ensure accuracy, maximum element size has been selected to be $\lambda_{min}/20$, where $\lambda_{min}$ is the smallest wavelength of interest. Elements’ theoretical optimal length has been calculated according to the Lamb Waves dispersion curves for S0 and A0 modes [15]. The excitation wave form is a 3.5 cycles tone burst windowed by a Hanning window.

### 3.1. Numerical results

Figure 4 shows normalized radial displacement amplitudes of the A0 and S0 Lamb wave modes from 0 to 400 kHz both obtained from the analytical models and from FEM simulations. As it can be observed for the A0 mode, a local maximum is located at approximately 75 kHz, and a minimum is located at 400 kHz, whereas the maximum amplitude for the S0 Lamb wave mode is located at 300 kHz. Therefore, optimal excitation frequencies should be between 50 and 75 kHz for tuning the A0 mode, whereas for tuning the S0 could be between 300 and 375 kHz. FEM results compare well with the theoretical models for both the A0 and the S0 modes, excepting a significant deviation for S0 from 25 kHz to approximately 125 kHz. Nevertheless, the optimal excitation frequencies determined considering both analytical and FEM results agree each other.

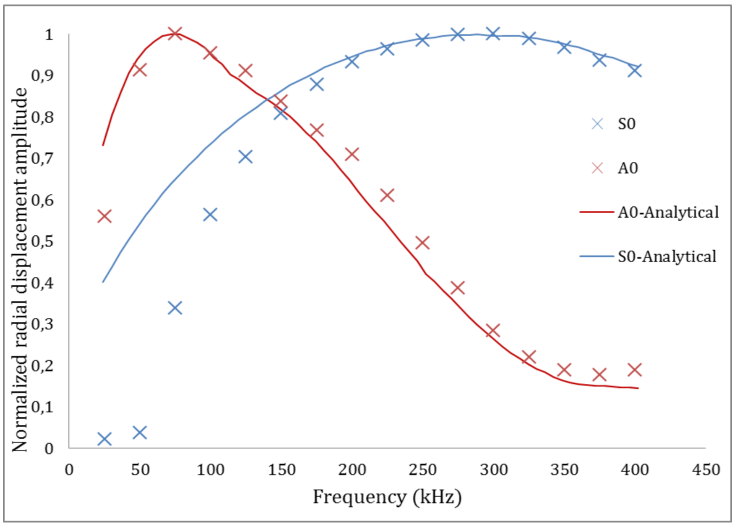


Figure 4: Normalized radial displacement amplitudes of the piezo-plate response.

## 4. NUMERICAL EVALUATION

In order to evaluate the proposed self-tuning method, numerical simulations have been carried out by the FEM. The FEM model is the same as the plate presented in section 3. The selected optimal excitation frequencies have been 50 kHz for the A0 mode and 375 kHz for S0 mode. The excitation wave form is the same as in section 2. The receiver array was a 12 mm-radius ring for the A0 mode, while for the S0 mode a 8.55 mm-radius ring was employed.

Figure 5 shows the simulated propagating wave front for a 50 kHz excitation. It is obvious that there is a dominant wave mode, which is the antisymmetric mode A0. It travels along the plate, and it is reflected when meeting the hole. The scattered wave front from the hole is detected by the ring array and it is processed by the DoA and the tomographic algorithm.

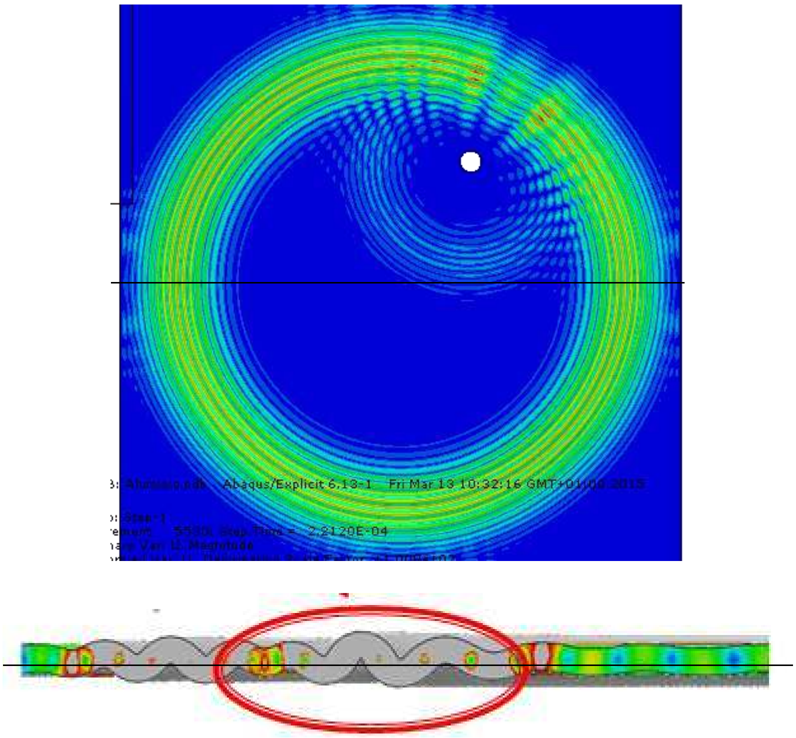

Figure 5: Wave front for a 50 kHz excitation (above) and plate section showing the generated antisymmetric A0 mode (below)

As it is shown on figure 6, recorded signals from the sensor nodes show three main bursts: the first time the wave front goes through the ring array, the reflected wave front from the defect, and the boundary reflection.

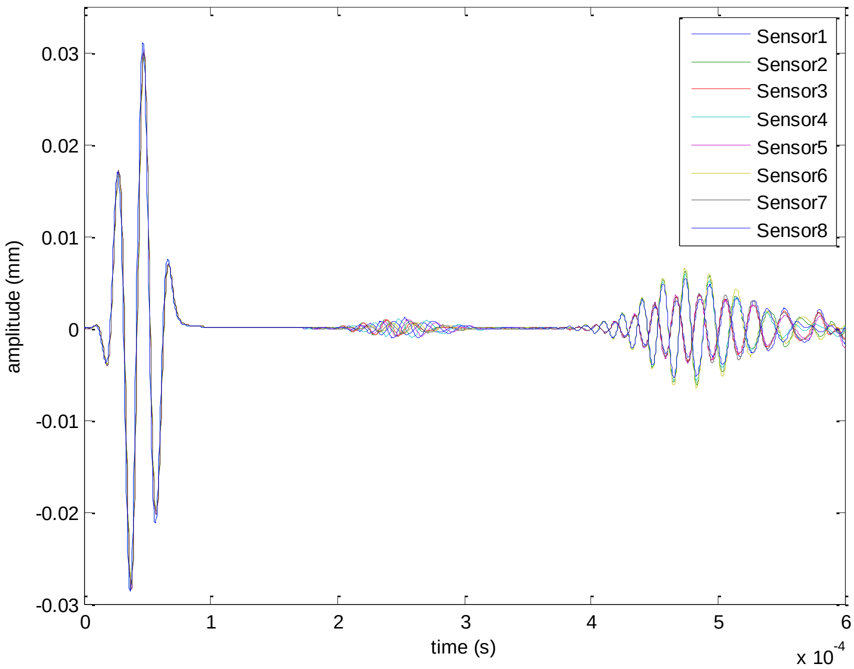


Figure 6. Recorded signals from sensor nodes

Once acquired signals are processed by the phase addition DoA algorithm and the reflection tomography algorithm, a B-Mode image is obtained displaying the damage location, as it is presented in Figure 7. As can be seen, the amplitude of the image on the damage zone (150 mm on $\varphi=60^0$ direction) is larger, so damage is located.

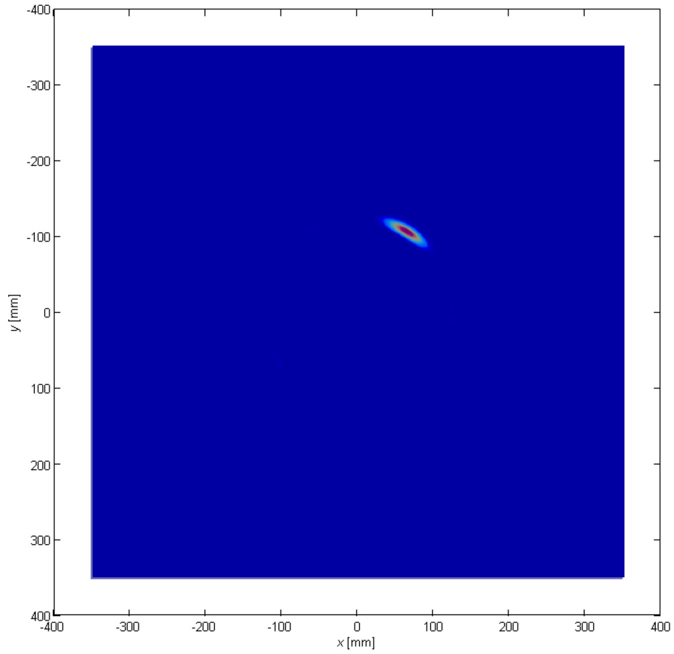


Figure 7. B-Mode image maximizing the A0 mode (50 kHz)

Figure 8 shows the signal measured by one of the sensor nodes of the array for the 375 kHz excitation. As it can be observed, the amplitude for the S0 reflection is considerably larger than the reflection due to the A0 mode.

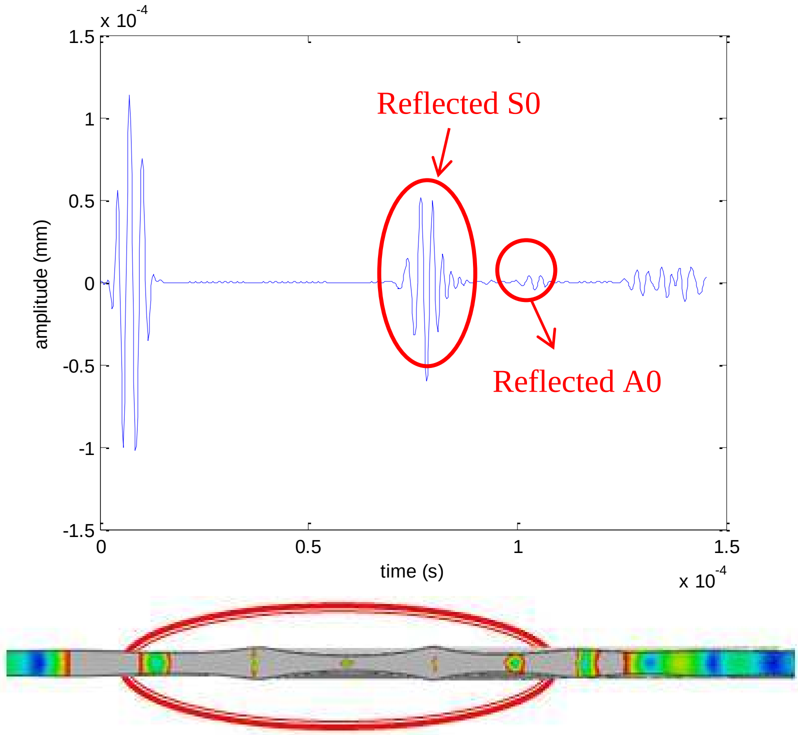


Figure 8. Reflection bursts for a 375 Khz excitation that maximizes the S0 mode (above) and plate section showing the generated symmetric S0 mode (below)

Figure 9 shows the B-mode image maximizing the symmetric S0 mode with a 375 kHz excitation. The damage of the plate is well-located, and comparing this image to the one obtained using the A0 mode, the damage location has a better spatial resolution, so damage is located more precisely. This is due to higher frequencies' higher resolution.

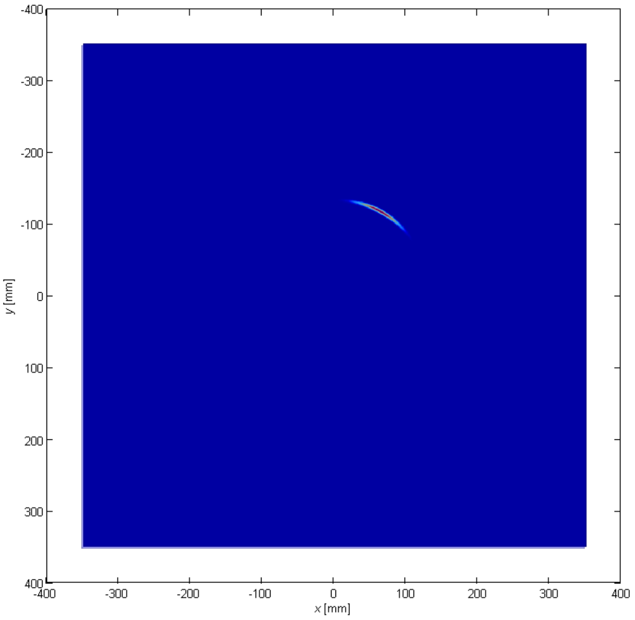


Figure 9: B-Mode image maximizing S0 mode (375 KHz)

## 4. EXPERIMENTAL VALIDATION IN AN AERONAUTICALLY GRADED CFRP PLATE

The proposed method has been experimentally evaluated in an aeronautically graded CFRP plate. A CFRP plate with a 1.5 mm radius hole located 100 mm away from the transmitter PWAS. The same procedure described in section 2 and 3 for selecting the optimal Lamb wave inspection frequencies, as well as the propagating velocities and attenuation in the different directions is employed. Only results obtained by inspecting the plate with the A0 mode are presented. This is due to the well-known fact that for higher frequencies, the excitation burst is filtered by local resonances near the transmitter PWAS that hinder the use of the S0 mode in our case. For the A0 excitation, an 80 KHz burst is selected. Noliac NCE51-OD10-Fr2Mhz-WAE piezoelectric discs were employed, both as transmitter and as receivers (see figure 10). For both exciting the transmitter and acquiring signals, the PAMELA ultrasound electronic system was employed. The PAMELA system has been developed by the AERNNOVA Company for SHM applications. Signals were acquired simultaneously with a sampling frequency of 12.5 MHz. Figure 10 shows the signal acquired by one of the receiver PWAS.

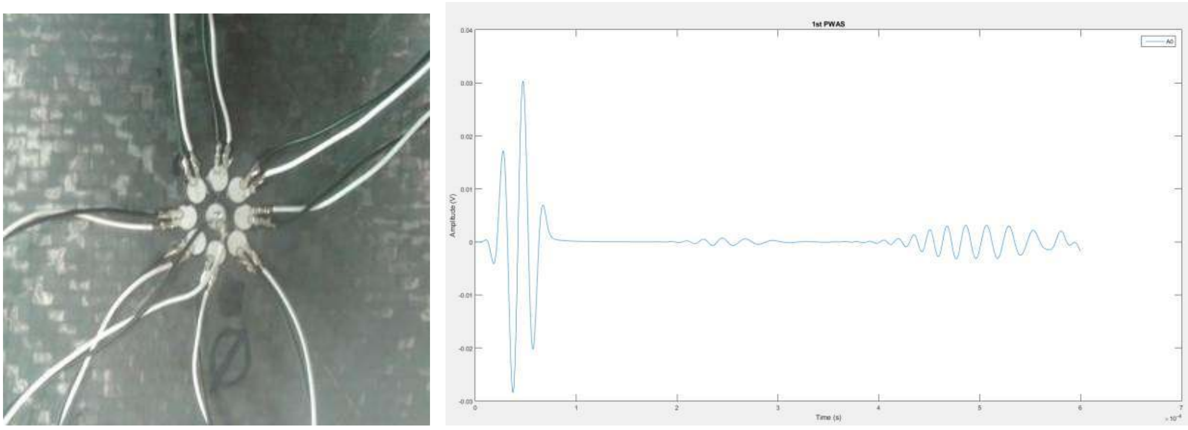

Figure 10. PWAS STMR ring topology (left) and signal measured by a receiver PWAS (right)

Acquired signals where processed by the phase addition DoA algorithm and the reflection tomography algorithm implemented in Matlab, the B-Mode image obtained displaying the damage location is presented in Figure 11.

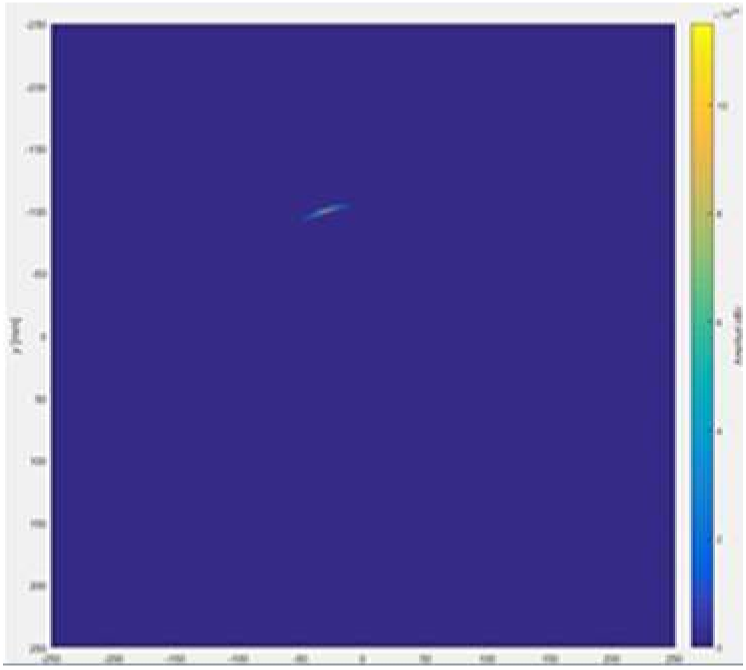

Figure 11: Experimentally obtained B-Mode image for a CFRP plate with a hole

## 5. CONCLUSIONS

A self-tuning method has been proposed for adaptively selecting optimum frequencies for inspections based on a specific Lamb wave mode, maximizing the aimed mode relatively to the rest of the modes. The importance of the frequency selection has been shown in this paper, to get the best possible results with only one mode.

The proposed method, based on a STMR ring topology can compensate different propagation velocities for different directions in anisotropic materials such as CFRP. The method can also tune the inspection parameters self-adjusting to variations in material properties due to fabrication or varying conditions such as temperature variations.

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