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ARRAY SIGNAL PROCESSING FOR CRACK DETECTION IN PLATES

A. Desoki*, M. Mahgoub† and H. Negm‡

ABSTRACT

The use of plate-like structures in the aerospace and energy fields demands thorough inspection during service due to the required high safety levels of operation. The structure strength can be affected by the existence of defects such as cracks, corrosion, composites delamination, etc. Structural Health Monitoring (SHM) using ultrasonic guided waves and active sensor arrays is a promising research area, especially in these fields. SHM develops a system which can interrogate the structure and listen to its response to detect whether its strength has been changed or not.

This paper examines the implementation of an advanced signal processing method to post process the array received signals and translate them into images that show defects. Simulation results showed that the proposed method yields good results as compared to another advanced but more complex method called Embedded Ultrasonic Structural Radar (EUSR)[1].

KEYWORDS

Structural health monitoring, SHM, crack detection, ultrasonic, array, beamforming, Multiple Signal Classification MUSIC, signal subspace,

NOMENCLATURE

BF	Beam Forming
DAS	Delay And Sum
EUSR	Embedded Ultrasonic Structural Radar
MUSIC	MUltiple SIgnal Classification
PWAS	Piezoelectric Wafers Active Sensors
SHM	Structural Health Monitoring
SNR	Signal to Noise Ratio
ULA	Uniform Linear Array

* Assistant Professor of Aircraft Structures, Aerospace Eng. Dept., Cairo Univ., ahmed.m.rashed@gmail.com.

† Aerospace Engineer, Master of Science in Aerospace Engineering from Aerospace Eng. Dept., Cairo Univ., ahmed.mahmoud.6582@gmail.com.

‡ Professor of Aircraft Structures, Aerospace Eng. Dept., Cairo Univ.

INTRODUCTION

SHM is interested in the observation of structural health over time with periodical readings using the measurements of sampled dynamic response from the sensors. These measurements are used to remove the damage-sensitive features. The statistical analysis of these features are used to conclude the current health condition of the structure [1].

SHM can be either passive or active [2]. Passive SHM utilizes passive sensors which can only listen to the structure. They do not interrogate it, and they are used only as receivers. The dependability of SHM increases when the used sensors can be used as transmitters and receivers. This type of sensors is called active sensors. Active sensors can interrogate the structure and also listen to its response. SHM that uses active sensors can detect the damage existence, position, size and intensity.

Conventional ultrasonic transducers are unsuitable for active SHM applications in thin-walled structures. These conventional transducers are replaced by Piezoelectric Wafer Active Sensors (PWAS). These sensors can be attached permanently in large numbers to the structure surface. SHM of thin-walled structure requires a special type of ultrasonic waves. These waves are called Lamb waves, which can propagate large distances with very little amplitude loss. This advantage facilitates the inspection of large areas from a fixed location. The Lamb waves can be generated and detected by the PWAS [3].

PWAS can be arranged in different array configurations. These configurations are 1-D linear array as in [3] or 2-D array as in [3]. The signals are emitted from the array and propagate until they are reflected by either the structure defects or the structure boundaries. The reflected signals are received by the array sensors and processed with one of the Direction of Arrival Techniques [6]. This signal processing extracts the signal source direction and position through an images. The quality of the these images depend on the configuration of the array, array sensor numbers, geometry of the sensor, wave propagating mode and post-processing technique [3].

Conventional array signal processing methods, such as the landmark Delay And Sum (DAS) Beam Forming (BF) method, are used frequently for crack localization. Despite its robustness versus noise, it has poor resolution [6]. Therefore DAS is hardly used as it is in SHM applications. Among improved array signal processing methods based on DAS is the EUSR method [1]. Despite its much improved results, it is considerably more complicated than the DAS. On the other hand, there are several other array signal processing methods [6]. This paper presents a step towards examining more advanced methods. As compared to DAS, the Signal Subspace Methods [6] have much better resolution as compared to DAS. The most famous method of this category is the MUltiple SIgnal Classification (MUSIC) method. In the following this method is compared to both the traditional DAS and the more advanced EUSR methods.

SIGNAL MODEL

Similar to radars, to localize the target (defect in our case) a wave signal is transmitted that travels through the medium (plate in our case) and reflects back at defects, if any.

Signals reflected at the defects are received at the transceivers array. Practically, Lamb waves are a good choice for plate like structures [3]. This can be achieved using an array of PWAS transceivers mounted to the plate surface. PWAS transceivers are commercially available and relatively cheap. Details are explained in the following.

For an array of PWAS transceiver, if one of the transceivers transmits a signal, it propagates omni-directionally through the plate passing through the existing defect (crack). The signal received at the crack is reflected back again to the sensor array, so that the m-th sensor measures

$$s_m(t) = \alpha_m u\left(t - \frac{l_m}{c}\right) + n_m(t) \tag{1}$$

where α_m is the attenuation factor of the signal reflected from the crack to the m-th transceiver, l_m is the distance between the positions of the transceiver and the crack, c is the wave propagation speed through the plate and $n_m(t)$ is the noise delivered by the m-th sensor.

These signals measured by the array sensors are processed by two array signal processing methods; the traditional DAS and the advanced MUSIC [6]. The results obtained by these processing methods are visualized as 2-D images to show the cracks position and distance from the array.

SIMULATION

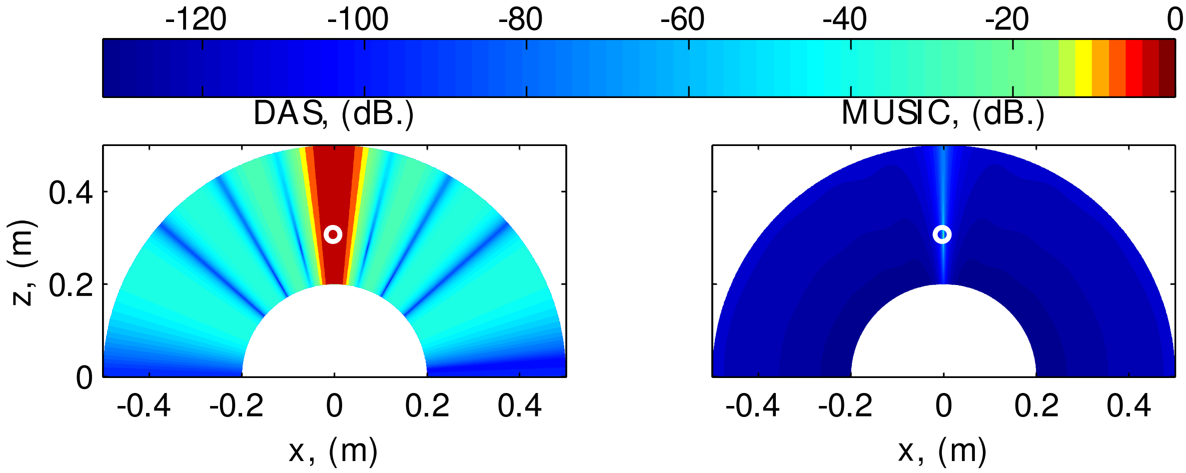
A Matlab code has been established to simulate the wave propagation and apply the DAS and MUSIC post processing methods to obtain 2D images showing the defect. In order to benchmark the simulation results, the same test specimens and sensor array configurations as in [1] are used. That is, a 1 mm thickness 2024-T3 Aluminum alloy plate and $M = 8$ sensors arranged in a Uniform Linea Array (ULA) are used. The array sensors are spaced by $d = 8$ mm ($\leq \lambda/2$ to avoid grating lobes). The Signal to Noise Ratio (SNR) of the array receiver measurements are set to 7.6.

For these configurations, the tuning frequency is $f_\mathrm{c} = 300$ kHz and the group velocity is $c = 5440$ m/s [1]. At this frequency, only the symmetric S_0 Lamb wave mode excites which yields much stronger echoes from a through-the-thickness crack than the A_0 waves [8]. Three wave cycles of Hann smoothed tone-burst excitation signals are used. A sampling frequency of $f_\mathrm{s} = 4f_\mathrm{c}$ is used ($> 2f_\mathrm{c}$ to avoid aliasing).

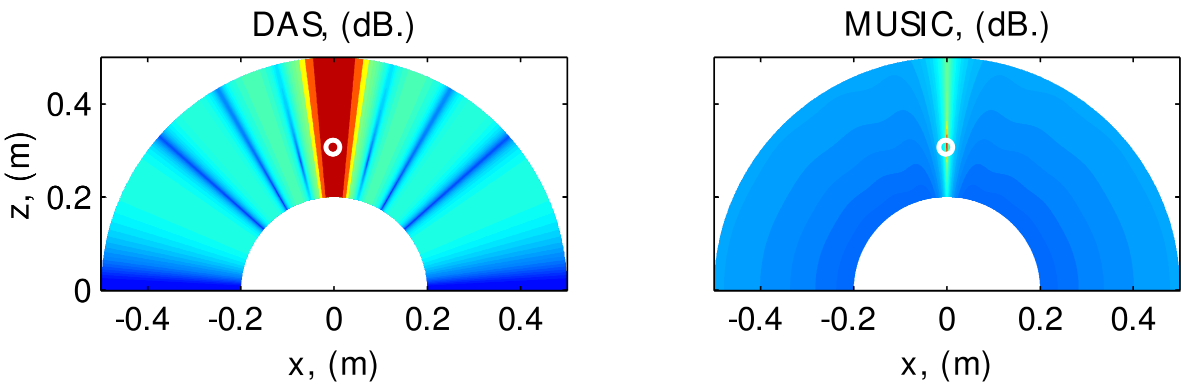
The crack examined is located at $z = 305$ mm. In order to show high resolution of the MUSIC method, a fine grid with $\Delta\theta = 0.25°$ and 100 radial steps is created. The grid spans the range $\theta = [0° - \frac{\Delta\theta}{2}, 180° + \frac{\Delta\theta}{2}]$ and $r = [200\ \mathrm{mm}, 500\ \mathrm{mm}]$. The angular grid span is shifted by $\frac{\Delta\theta}{2}$ in order to prevent grid points from coinciding with cracks located at whole number values of θ.

The crack is simplified as a point source. For detecting this crack, the first sensor in the array transmits the excitation signal described above. This signal is reflected at the crack back to the array sensors to obtain the measurements described by equation (1).

If the point crack coincides with one of the scanning area grid points, MUSIC detects the crack with best resolution, as shown in Figures 1(a), 2(a) and 2(c), whereas DAS can only detect the crack angle rather than the radial distance. For the normal case where the point crack does not coincide with a calculation surface grid point, the results of figures 1(b), 2(b) and 2(d) are obtained. As clear from these figures, MUSIC still has superior resolution as compared with DAS. In fact DAS failed to detect the crack radial distance.



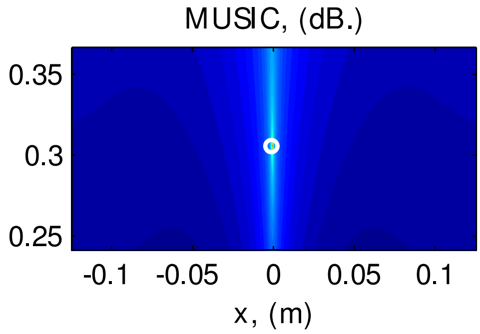
(a) Point crack at $\theta = 90° + \frac{\Delta\theta}{2}$ (best case of a point crack where a grid point coincides with the point crack).



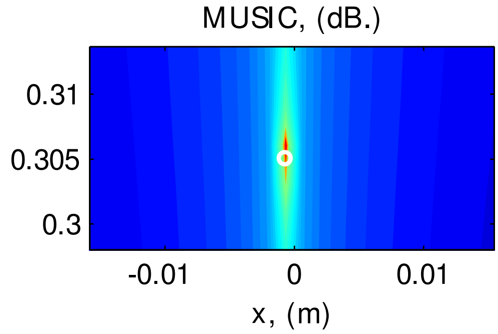
(b) Point crack at $\theta = 90°$ (normal case of a point crack where grid points surround the point crack).

Fig. 1. (left) DAS and (right) MUSIC fields of a point crack.

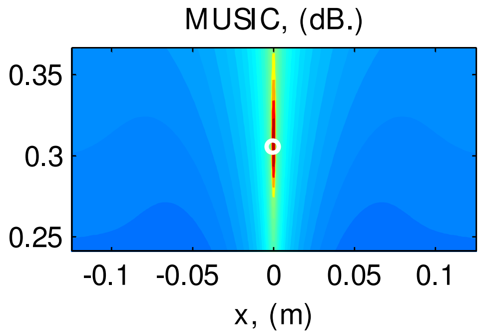
Fig. 3 shows the EUSR fields obtained for a real experiment. As shown from the figures, EUSR failed to detect the pin holes of diameters less than 1.57 mm. Beginning from this hole size, EUSR gave precise indication for the pin hole location. This hole diameter was considered as the minimum detectable damage dimension at this inspection frequency.



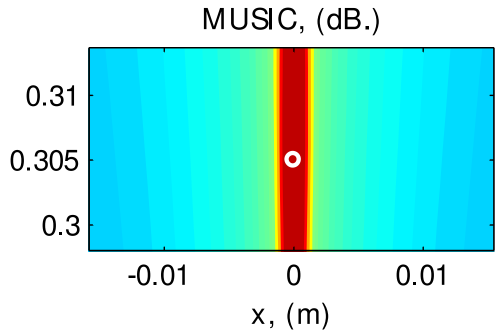
(a) 4x zoom of rhs of figure 1(a)



(c) 10x zoom of rhs of figure 1(a)



(b) 4x zoom of rhs of figure 1(b)



(d) 10x zoom of rhs of figure 1(b)

Fig. 2. (left) 4x zoom (right) 10x zoom of rhs of Figure 1.

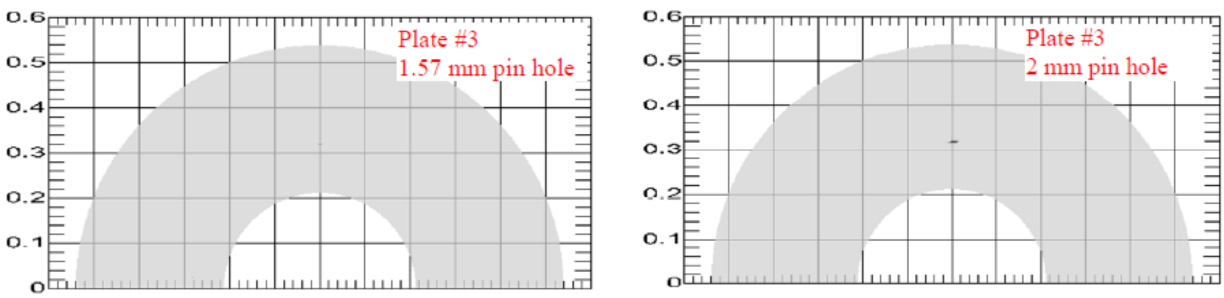


Fig. 3. EUSR field of a point crack (left) 1.57 mm pin hole, (right) 2 mm pin hole (copied from [1]).

CONCLUSION

As was shown in this paper, signal subspace based methods are very promising for crack detection, as compared to the traditional DAS. That is, signal subspace based methods can yield a much better angular resolution for defects. The radial resolution however is not as good as the angular resolution. However it is still much better than DAS which fails to radially locate the crack altogether. In fact, it can be argued that the decreased radial resolution of the examined signal subspace method is a property of the ULA rather than the proposed method.

The advanced DAS-based EUSR method on the other hand completely fails to experimentally detect pin holes of diameters less than 1.57 mm. Simulations of the chosen signal subspace method on the other hand does not have this limitation and can easily detect a theoretical zero diameter hole using a much less array signal processing. In the near future the MUSIC method will be applied to a real experiments for additional verification of the difference between its experimental results and the experimental results of other methods like EUSR.

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