An optimization strategy for best sensor placement for damage detection and localization in complex composite structures

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Abstract
In this paper an optimization strategy based on providing maximum area coverage (MAC) resulting in optimal sensor placement for damage localization in complex composite structures is proposed. The proposed optimization algorithm is uses genetic algorithm to minimize the defined fitness function based on geometrical and physical constraints of the structure, rather than probability of detection of the damage detection algorithm. The proposed fitness function is applicable to any damage detection technique based on ultrasonic guided wave in pitch catch configurations and is readily up-scalable to any structure. The optimization algorithm is then applied to a full wing demonstrator of an aircraft.

1 INTRODUCTION

Structural Health Monitoring (SHM) techniques have gained much interest in the recent years as potential means to progress from scheduled based maintenance towards condition based maintenance, resulting in significant cost reductions. For any developed SHM technique, to be applicable as a maintenance strategy to real structures, it must demonstrate 90 probability of detection (POD) with 95% reliability. While the SHM system must have high reliability, it must also have the minimum interference with the structural functionality in terms of added weight. Therefore optimized transducer number and location is a key factor in the design and uptake of any SHM system. The Piezoelectric transducers, PZTs, due to their electro-mechanical coupling can be used as both sensors and actuators making them suitable for both passive [1-3] and active sensing [4-11]. The application of guided waves for impact and damage detection is well established for simple plates or pipes [12]. A challenge in upscaling the developed methodologies is in separating the mod-superposition and boundary reflections and those originating from damage. For aeronautical application the focus is given to plate-like structures with complex geometries (stiffeners, frames, man-holes)where the optimal transducer configuration may not be so trivial [13]. Therefore the reliability of any SHM system for complex structures such as aircraft composite panels is directly linked with successfully determining the best actuation signal and optimal sensor positions for complex structures.

Numerous studies are focused on sensor optimization for defect detection in metallic structures [14-16]. Several studies have looked at the effect of the sensor pattern distribution on the overall damage detection capabilities with guided waves .Most of the optimization approaches are based on maximizing a POD function related to impact and/or damage detection [17, 18]. The determination of POD for metallic structure is well-established and it requires a vast number of damage scenarios (various location and severities) for every structure. To generate the library of the required data for large complex structures (either numerically or experimentally) is too expensive. For damage detection and localization in composite structures there are no fixed guidelines to define a POD function, therefore the application of the optimization algorithms based on the POD to composite structures is limited. Another disadvantage is that for each damage detection technique a different POD function is introduced and this means by changing any details in the damage detection algorithm it will result in a different optimal sensor positioning.

Therefore, this paper aims to propose a sensor placement optimization approach, for damage detection and localization with guided waves which is not directly related to the details of the damage detection algorithm nor the evaluation of the POD. The proposed algorithm is based on maximum area coverage (MAC) within a sensor network which can be applicable to any complex structure with pitch-catch sensor configuration and any active sensing algorithm based on triangulation. In this paper, the applicability of the proposed optimization strategy to a composite wing demonstrator is presented.

2 FITNESS FUNCTION

Any optimization algorithm will search to minimize a defined fitness function. In this case, the introduced fitness function must best represent the performance of sensor network in localizing damage at any point in the structure. The unique fitness function introduced in this work is based on the physical and geometrical constraints of the structure and Lamb wave propagation characteristics, by indicating the maximum area coverage as well as the intensity of the coverage [19]. The advantage of such a fitness function is that it is independent of the details of the damage detection algorithm and does not require a large data base of damage detection cases for constructing the POD. In this section the key parameters in constructing the fitness function are presented.

First a brief description of damage detection with ultrasonic guided wave (UGW) is presented here in order to highlight the physical and geometrical constraints which are the contributing factors to the performance of any SHM system.

2.1 Damage detection with UGW

There are different algorithms based on guided waves for detecting and/or localizing damage. The aim here is to focus on active SHM systems which are suitable for detecting and localizing damage in large complex composite structures such as aeronautical panels. Therefore, detection algorithms suitable for composite structures with a network of transducers positioned in a pitch-catch configuration and interrogated in a round-robin approach is chosen. The basic idea of the pitch-catch configuration and triangulation approach is that the presence of damage in the structure causes reflection and refraction of the wave. By comparing the changes in the propagation of the wave in presence of the damage to a pristine state (based on the time of flight, ToF, of the damage reflected wave) damage can be detected and localized via fusing the results from all transducer paths. Damage detection with Pitch-catch configuration assumes the first residual peak to be generated from damage reflection, therefore it is required for the damage to be present inside the network area for it to be detected and located with high probability and reliability [20]. Therefore one important factor in the development of the fitness function is maximizing the area covered inside the transducer network.

Once all the transducer pairs have been interrogated, a diagnostic imaging algorithm is adopted to visualize the probability map of damage location based on the damage index (DI) values fused from all paths [21] This means that the detection algorithm is dependent on the group velocity of the propagating wave. The proposed detection algorithm can be applied to isotropic [22], quasi-isotropic [23] and anisotropic [24] plates based on the group velocity of the actuated wave. The imaging algorithm divides the structure into pixels where the DI is calculated at the center of each pixel based on the ToF of the propagating wave. An example of the DI measurement for a pixel D (possible damage location) is shown in Figure 1. Each actuator sensor path results in a probability distribution based on the measured DI for all the pixels in the structure and all images fused together to present the most probable damage location.

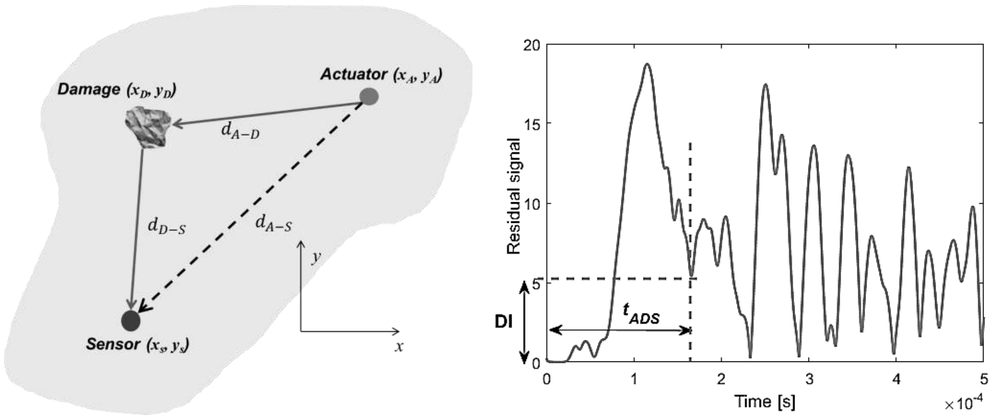


Figure 1: Example of DI measured at a pixel based on ToF of damage scattered wave.

The main challenge of a damage detection algorithm based on the ToF of the damage reflected wave is to be able to isolate the damage scattered wave from the other sources of reflection such as the boundaries of the structure (physical boundaries of the structure, stiffener, frames, and openings) as well as mode superposition which can corrupt the signal. Even though several methods have been developed to minimize these negative effects, their applicability is limited to aluminum panels or simple composite plates [13, 25].

If the transducers are placed too close to the boundary, for a given probable damage location D, the ToF measured from the residual signal locates the probable damage position in form of an ellipse, with the two transducers being the foci. In this case, the damage reflected waves and the boundary reflected waves can coincide resulting in reduced reliability of the damage detection algorithm, see Figure 2. Consequently the introduced fitness function takes into account the effect of boundary reflections and aims to position the transducers to minimize the negative effects.

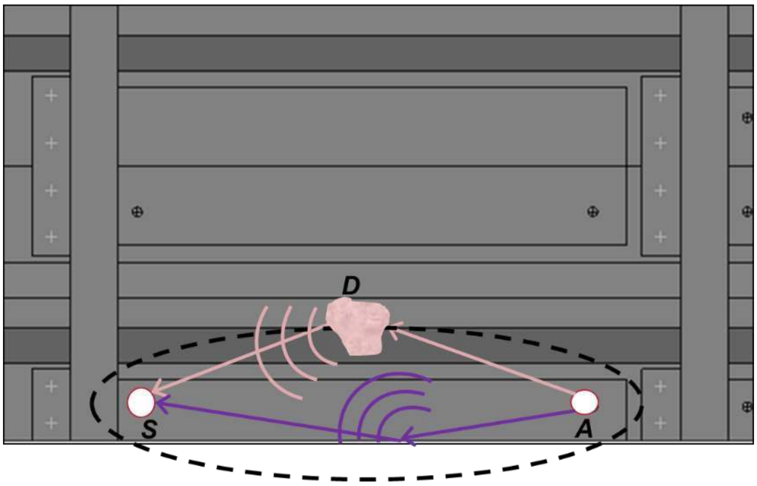


Figure 2: Example of an ellipse pixels partially included within the boundaries.

2.2 Global fitness function definition

In this paper a global fitness function is introduced based on maximizing the coverage area provided by a sensor network and by applying physical and geometrical constraints [19]. First the structure is divide into pixels. Then for each pixel, all the transducer pairs resulting in constricting an ellipse passing through its center are considered to contribute to the intensity of the coverage at that point. This will be carried out for each pixel and summed for each transducer path. The higher the number of ellipses passing through a pixel, the higher the probability of locating damage at the given location. Given a total of N transducers, the number of ellipses crossing each pixel is given by $N = N(N-1)$. Without introducing additional constraints to this condition, all the pixels in the structure will have uniform probability of detecting damage as for every point given a transducer pair an ellipse can be constructed. Therefore, geometrical and physical constraints are introduced in constructing the fitness function.

The first geometrical constraint introduced is to limit the boundary reflections. In this case the boundary can either be the physical boundaries of the structure or parts such as stiffeners or frames. For each pixel, the ellipse which passes through that point is constructed and the length of the ellipse which falls outside of the boundaries, l_{bound}, is measured. If this value is above a certain threshold the ellipse will not be included in the fitness function evaluation (coverage index CI=0 for that pixel), otherwise the ellipse will have a positive contribution and the CI for that pixel and that transducer pair=1.

$$CI(pix, path) = \begin{cases} 0 & if \quad l_{bound} \geq \gamma * l_{tot} \\ 1 & if \quad l_{bound} < \gamma * l_{tot} \end{cases} \tag{1}$$

Every transducer pair produces a binary image. The global coverage of the structure is then obtained by summing all the coverage indices produced by each transduce path.

$$cov(pix) = \sum_{path=1}^{N(N-1)} CI(pix, path) \tag{2}$$

The choice of the reflection coefficient γ is up to the user based on how well their damage detection algorithms can minimize the effects of the boundary. Throughout this work $\gamma = 0.25$

has been chosen.

So far the fitness function has been based on geometrical constraints. However, there are physical properties related to the wave propagation in a structure which influences the damage detection and hence the optimal sensor placement. One of these factors is the group velocity. In anisotropic plates, the probable damage locations for each transducer paths will be based on the directional velocity of the propagating wave. Therefore, for each pixel to construct an ellipse this directionality of the wave propagation will be introduced in terms of a shape parameter. Another important physical factor is the attenuation of the guided wave. The relationship between the actuation frequency and attenuation of Lamb waves is well established [7]. Different frequencies have different low of power per unit distance, therefore depending on the range of the frequencies which the SHM is designed to be functioning, this influence should be integrated in the coverage area. This is of particular interest for large structures where the distance between the transducers are great or when the wave propagates through stiffeners and frames which also result in dissipating energy. The first step requires to obtain the attenuation profile of the structure for its range of the operational frequencies. This factor is then introduced in terms of the distance from the actuator to a pixel. Once the attenuation profile is available, for each pixel, the coverage index can be weighted based on the attenuation profile. The coverage index from all pixels are then fused together to obtain a single value representing the network performance.

$$c = \sum_{pix=1}^{nr_{pixel}} cov(pix) * \text{atten\_factor} \tag{3}$$

The best network performance is reached when c is maximum. Usually, optimization algorithms search for local or global minimum. In addition for the pitch catch configuration there is a higher probability of detecting damage when is positioned inside the transducer network. Therefore the global fitness function is determined as:

$$F = \frac{1}{c * A_{network}} \tag{4}$$

where $A_{network}$ is the area included inside the network of sensors. Depending on the network configuration, different values of F can be obtained.

The philosophy of the proposed optimization strategy is to search the optimal positioning of transducers for a given minimum number which results in a maximum coverage map. The user then has to decide, based on the POD of damage detection and localization which is required, whether the coverage is acceptable. If not, the number of transducers will then be increased and the optimal sensor positions searched again.

3 OPTIMIZATION

Once, the minimum number of sensors, N, is chosen then an optimization algorithm will search for their optimal positioning based on the introduced fitness function. In theory, the transducers are free to be placed at any location within the structure. However, to optimize the search, practical engineering constraints are added to the algorithm to ensure realistic positioning of the sensors. Examples of these constraints are in terms of the minimum edge distances from boundaries, minimum distance between the transducers, and ease of access in that part of the structure. Therefore a vector of all possible sensor positions, P, can be constructed. The total number of possible networks made of N transducers with P number of possible positions are evaluated as:

$$NET_{tot} = \frac{P!}{N! * (P - N)!}$$

An exhaustive search is not an option for even small structures dues to many possible scenarios. Therefore, Genetic Algorithm (GA) which reduces the number of computation significantly, has been adopted in this paper. The details of the GA can be found in [19] and its parameters have been chosen following a thorough parametric study following [18] ensuring convergence. To show the applicability of the proposed optimization strategy, it has been applied to a full composite wing demonstrator [26].

3.1 Example

The composite lower wing panel depicted in Figure 3 is sensorized with 133 piezoelectric transducers. This test was carried out as part of the SARISTU project.

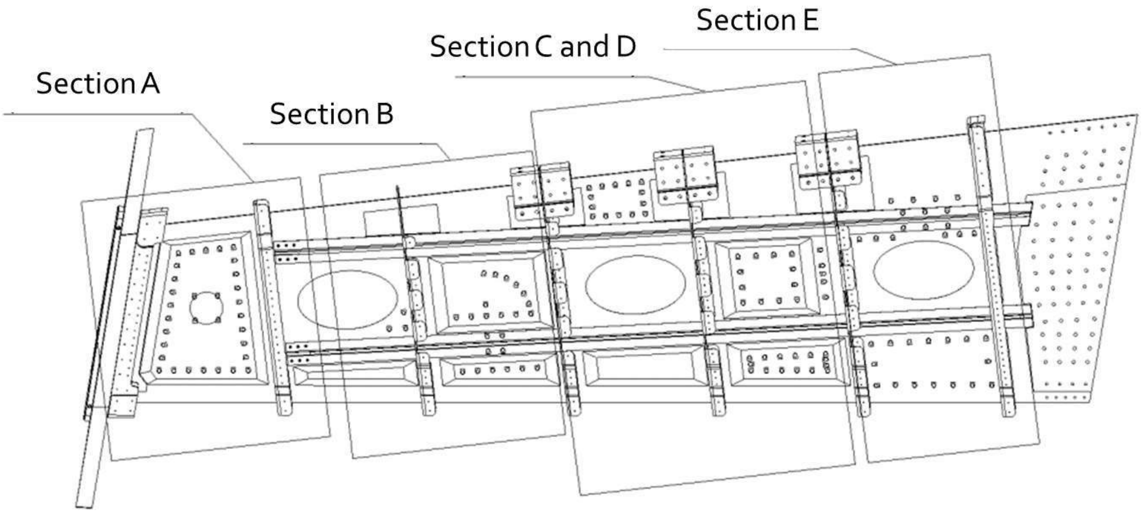


Figure 3: Lower wing box panel with all possible sensor positions - SARISTU project [26]

The lower panel is divided into 5 sections each with different transducer configuration. The wing panel has been over sensorsized for obtaining a large library of data base signals. Therefore it is a good study case of application of the optimization algorithm. Moreover, experimental data are available to obtain the physical parameters such as attenuation profile. From the numerical assessment of the damage detection methodologies applied to the wing demonstrator, it was concluded that the minimum number of transducers to reliably detect damage in each section is 8 [26]. Therefore the best 8 transducer locations for each section has been searched. The optimization was carried out for each section and each group individually for several runs to ensure convergence. The final optimal sensor locations for the full wing panel, together with the extent and intensity of the coverage has been plotted in the same scale in Figure 4. It can be seen that the sections where the density of the sensors are higher, section A, have a much higher intensity in terms of coverage area than other section with a sparse array of sensors, e.g. section B. This is a good indication of the relation between the coverage area and intensity.

The results of some of the sections are further detailed below for better clarity.

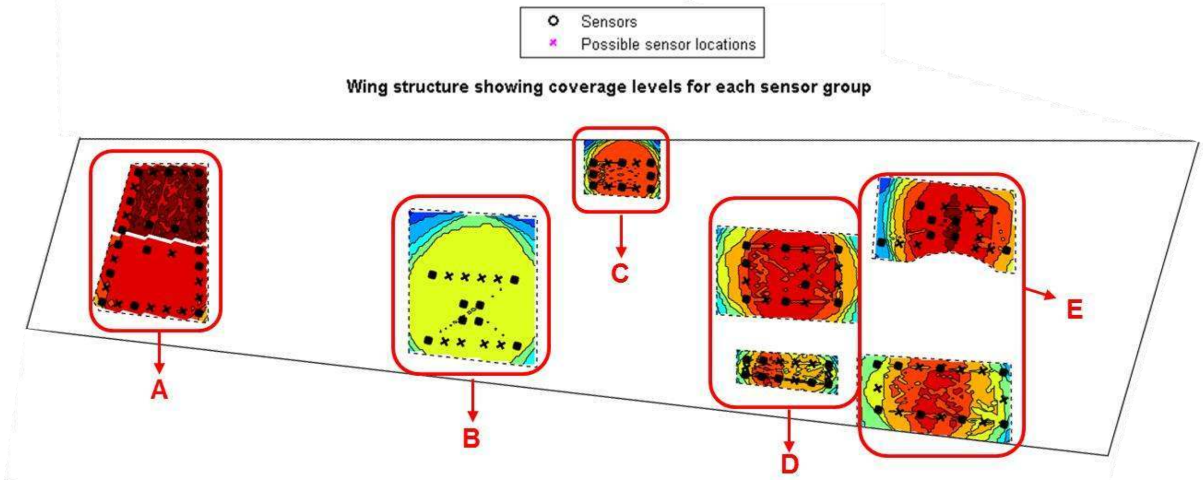
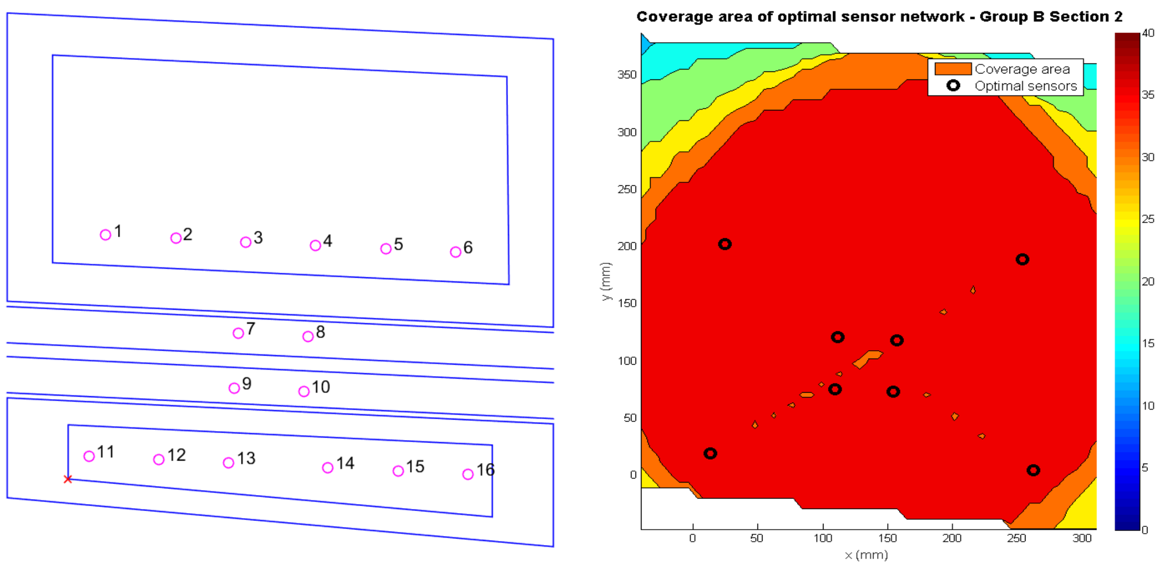


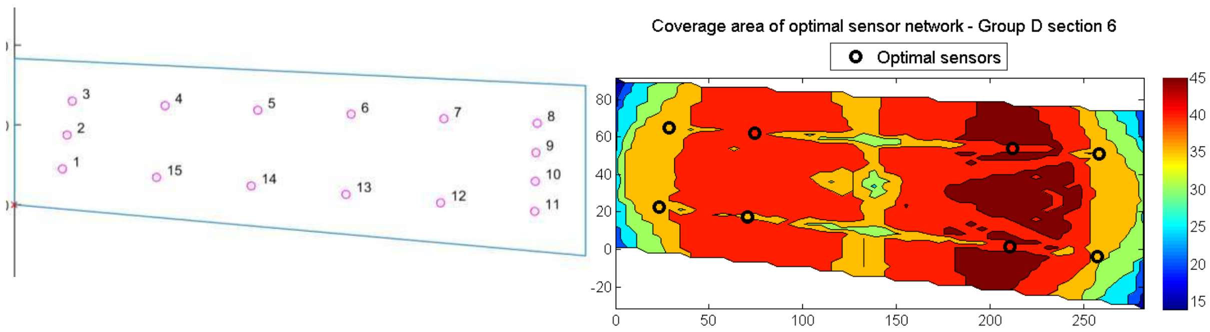
Figure 4: coverage map together with optimal sensor positions for the lower wing panel

The plots in Figure 5 shows the optimal sensor position for a part of the lower wing where there is a stiffener present, section B. This is good implication that the optimization strategy is applicable to complex structures with stiffeners and frames.



(a) All possible sensor location (b) Optimal 8 sensor locations

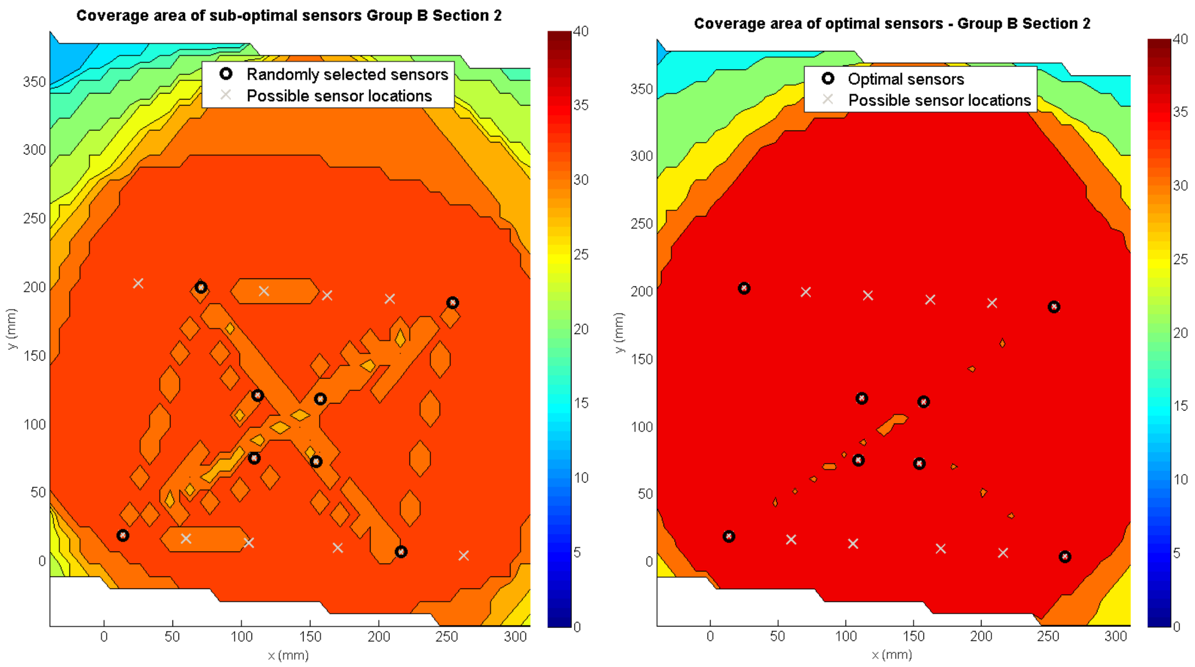
Figure 5: Optimal sensor placement – Section B



(a) All possible sensor location (b) Optimal 8 sensor locations

Figure 6: Optimal sensor placement – Section D- bottom

To validate the optimal sensor positioning, the coverage map area and intensity of the optimal sensor network is compared to several sub-optimal networks chosen at random. Some of the results are presented in



(a) Coverage area of sub-optimal sensors randomly selected

(b) coverage area of optimal sensors resulted from the optimization

Figure 7: verification of the optimal sensor positioning

9 CONCLUSIONS

In this work, a novel optimization strategy based on a fitness functions resulting in maximum area covered (MAC) has been proposed. The introduced strategy is based on the geometrical parameters of the structure and the physical factors of the ultrasonic guided wave propagation. Therefore, it does not require a large data base for constructing the POD function. The applicability of the proposed optimization has been demonstrated on a full composite wing demonstrator where complexities such as stiffeners, frames, varying thickness and openings were present. The optimization has resulted in optimal sensor locations which can be verified by numerical/experimental examples. The proposed methodology can be readily applied to any structure with complex geometries.

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