THE USE OF PSEUDO-DEFECTS IN VALIDATION OF ULTRASONIC STRUCTURAL-HEALTH-MONITORING TECHNOLOGIES

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INTRODUCTION

When new ultrasonic techniques for non-destructive testing are introduced, diverse validation tests are required. Signals obtained from samples with well-characterised natural defects (cracks, flaws) or artificial defects (notches, boreholes) are compared with signals obtained from undamaged samples, and so the NDT technique can be assessed towards reliability and accuracy. That concept finally leads to calibration procedures for ultrasonic systems. Distance/Gain/Size (DGS) - diagrams e.g. give an indication on the size of defects for flaw detectors, and dedicated test blocks are e.g. used to calibrate the ultrasonic thicknesses gauges for different kinds of material [1]. The traditional procedures are however only applicable if relatively simple samples are present. If the complexity of the investigated parts concerning shape and material composition is increasing, also the efforts for NDT validation tests increase. This is especially the case when structural health monitoring (SHM) systems for structural aircraft parts have to be validated.

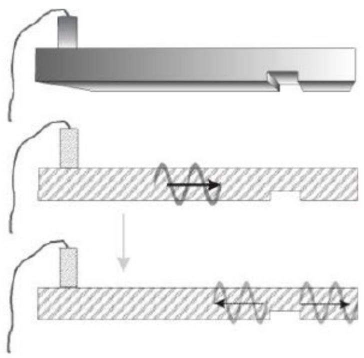
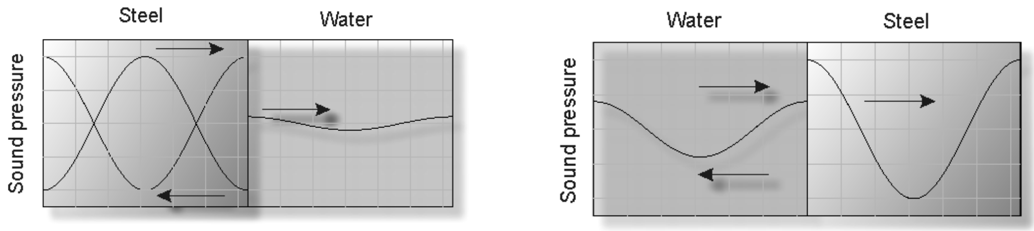


Figure 1 Idealised representation of defect detection using guided ultrasonic waves (Lamb waves)

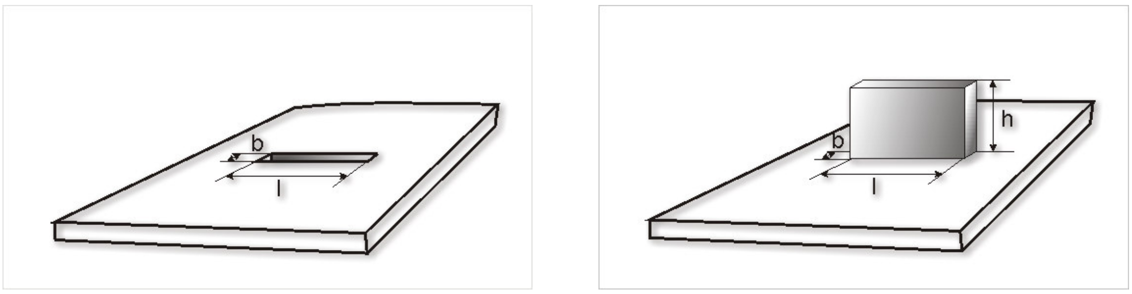
Due to the dominance of plate-like structures in aircraft, guided plate waves (Lamb waves) are interesting candidates for such automated inspection systems (Figure 1). However, the guided waves have to be monochromatic due to the dispersive nature of Lamb waves. The approximate monochromacy results in signals that are represented by sinusoidal waveforms which are quite broad in the time and the spatial domain (typically consisting of 5-10 cycles) compared to the short pulses used in classic ultrasonics. The most appropriate frequency for Lamb waves is e.g. in the range of 400 kHz for a given aluminium sheet with a thickness of about 1 mm (see e.g. [2]). The corresponding group velocity of the appropriate S_0 mode is about 5400 m/s, and this yields a wavelength of about 13,5 mm. A waveform consisting of 5 sinusoidal cycles has therefore a spatial length of about 70 mm. However, in many aircraft structures, there are in a circle of about 10 cm almost no areas available without diverse "natural" reflectors (stiffeners, lap joints and rivets) hindering the free wave propagation of Lamb waves. This leads finally to multiple reflections that will interfere with the waves caused by real defects. Moreover, reflections are usually accompanied by mode conversions and this additionally complicates the analysis of the experimental data.

Due to the complex nature of the ultrasonic signals, signal analysis means in many cases that incremental changes of the signal with respect to a reference measurement are analysed (baseline method). This is in contrast to classic ultrasonic NDT, i.e. the traditional determination of e.g. the material thickness or the damage size must be possible, independent of earlier data determined at the same undamaged sample. In the case of SHM, it is thus important to perform measurements of the undamaged or less damaged part in order to follow-up the progress of the degradation process to obtain some kind of novelty parameters. It is self-evident that every complex part shows its own baseline behaviour, and therefore, the baselines and defect parameters obtained at the validation phase must not necessarily be valid for the respective structure in another aircraft. The baseline method thus challenges in principal even the feasibility of the validation of SHM by artificial or real defects.

a)



b)



c)

Figure 2 Real notch and pseudo-defect for creating similar reflections

Defect detection follows the concepts shown in Figure 1. Waves interact with defects and this leads to specific reflection and transmission characteristics. Classic detection by pulse-echo can in a first approximation be explained by the reflection of a plane wave at the interface between sample and air/vacuum (or sample and water) whereby the defect is represented by the volume with the lower acoustic impedance (Figure 2). This is analogous with the rope reflection at a lose end.

The basic idea presented here is to replace real defects by non-destructively applied pseudo-defects. To achieve this, the material is subjected to a non-destructive modification. In the present case, this is done by two blocks that are modestly pressed onto both sides of a thin plate (Figure 2, c). This modification of the material leads to specific reflection and transmission characteristics which is similar to certain real defects, if the dimensions of the blocks are adequately chosen. Such as in the case of real defects, the reflection of Lamb waves at artificial pseudo-defects is in principal correlated with local changes of an apparent acoustic impedance.

The reflection and transmission of Lamb waves is on a theoretical level much more difficult to describe than in the case of bulk waves. One of the problems arises from the fact that guided waves can be considered as superposition of numerous elementary waves that irradiate the material interfaces at different angles. This results in all different kind of mode conversions. In the case of Lamb waves, the reflection coefficients are a function of the wave number and the plate thickness and normally, reflections coefficients are often smaller than 1, even in the case of edge reflections. For a more detailed analysis of the reflection of Lamb waves at defects see also e.g. [3-5].

Until now, no literature was found referring to systematic studies on such pseudo-defects to be used in SHM validation tests. But one might have a look at similar studies that were published addressing the theoretical and experimental treatment of similar cases. Song et al. [6] considered the scattering of Lamb waves at plate overlaps. The corresponding reflection and transmission characteristics show indeed strong dependency on the frequency and the Lamb mode. Practical NDT applications thus require a thorough tuning to find optimal reflection and transmission conditions. Similar conclusions were drawn in a study on thickness variations in thin sheets Cho [7] and lap shear adhesive joints [8]. The strong dependency on frequency shows that tuning is an essential part during the establishment of baselines.

Finally, non-destructively applied pseudo-defects potentially enable a huge number of learning cases for advanced data analysis of ultrasonic data when the testing objects are rare, too complex or too expensive. The principle is illustrated in the lower plot of Figure 2, c. At the left side, a natural crack in an infinite aluminium plate with a defined thickness, d is modelled by an artificial notch with the length l and the width b. The corresponding pseudo-defect would be blocks with a height h which are pressed onto both sides of the surface having the respective dimensions l’ and b’. The principal question are similarities and differences of the transmission/reflection characteristics for both cases.

MATERIALS AND METHODS

The concept is shown in the following experiment; an aluminium plate was used with a side length of 1 m was used to suppress disturbing side wall reflections. Piezoceramic patches were attached in an array by cyano-acrylate adhesive (M-Bond 200). The optimum frequency was in the range of about 350 kHz. The actuators were driven by an arbitrary waveform generator at a frequency of 350 kHz. The output signal consists of bursts (5 counts at an output voltage of 10 V_{pp}). The signals were received by the respective sensors and used without pre-amplification.

The resulting wavelength would be of the order of 13,5 mm. In order to check the detection capabilities with respect to defect locations, 9 piezoelectric transducers were arranged in one line so that they could be used in a passive phased-array mode (comparable to [9, 10]). The sensors (APC ceramics) had a thickness of 0,2 mm and a side length of 7 mm, and the distance between the sensor was 9 mm which is approximately in the range of a half wavelength.

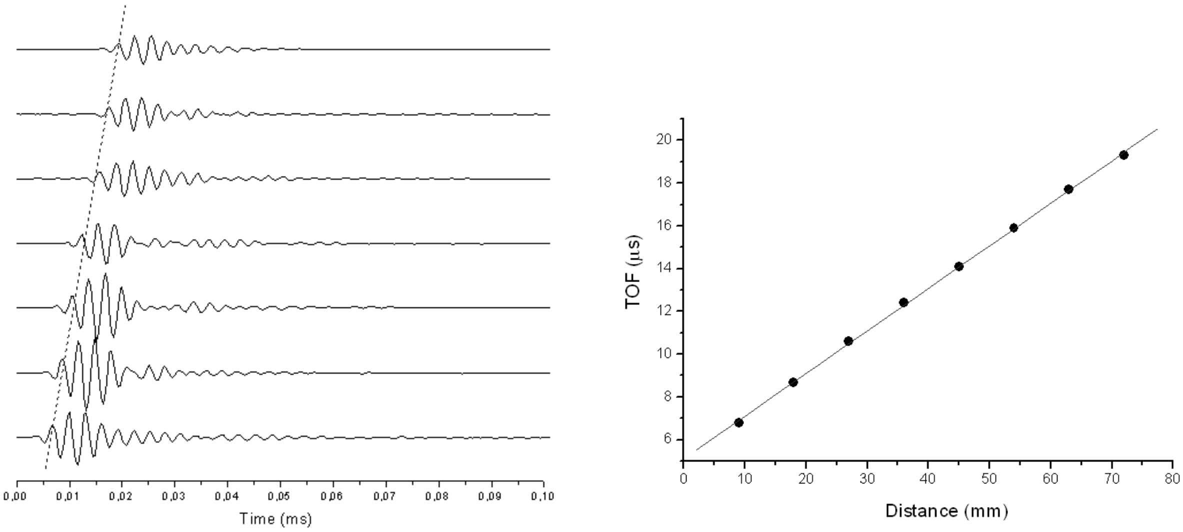


Figure 3 Determination of the group velocity (Time of arrival versus distance) using the different sensors of the phased-array sensor

Firstly, the sensors were tested and due to the different positions, the group velocity in the array region was determined to be about 5020 m/s (Figure 3). This value is important for the mathematical procedure to determine the position of the pseudo-defect using the 2D plot.

RESULTS AND DISCUSSION

Blocks with different sizes, positions and orientations were fixed by a screw clamp (Figure 4). It appeared that the pressure applied to the blocks had no influence on the reflection pattern once a certain pressure threshold was reached. The detection of the position is possible by using of the 2D plot (Figure 5, right).

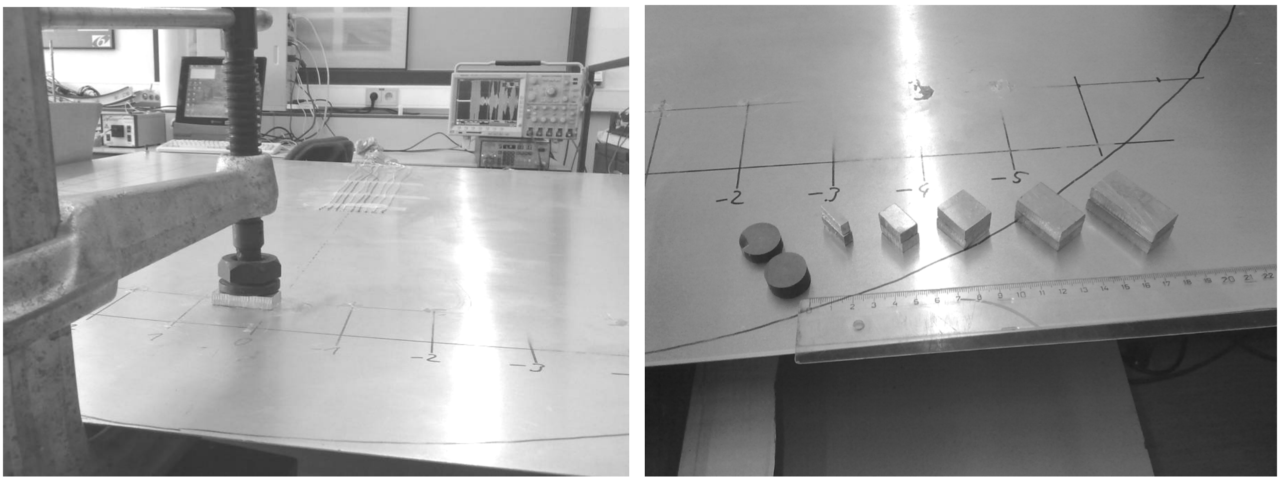


Figure 4 Left) Screw clamp to apply pseudo-defects. At a distance of about 40 cm an array of piezoceramic patches is attached. Right) Different pseudo-defects used for an undamaged aluminium plate. The width and height of the pseudo-defects were 15 mm and 10 mm resp., and the length varied between 5 mm and 40 mm.

The most important feature is that the pseudo-defects gave clear echo's that completely disappeared when the pseudo-defect was removed (Figure 5, left).

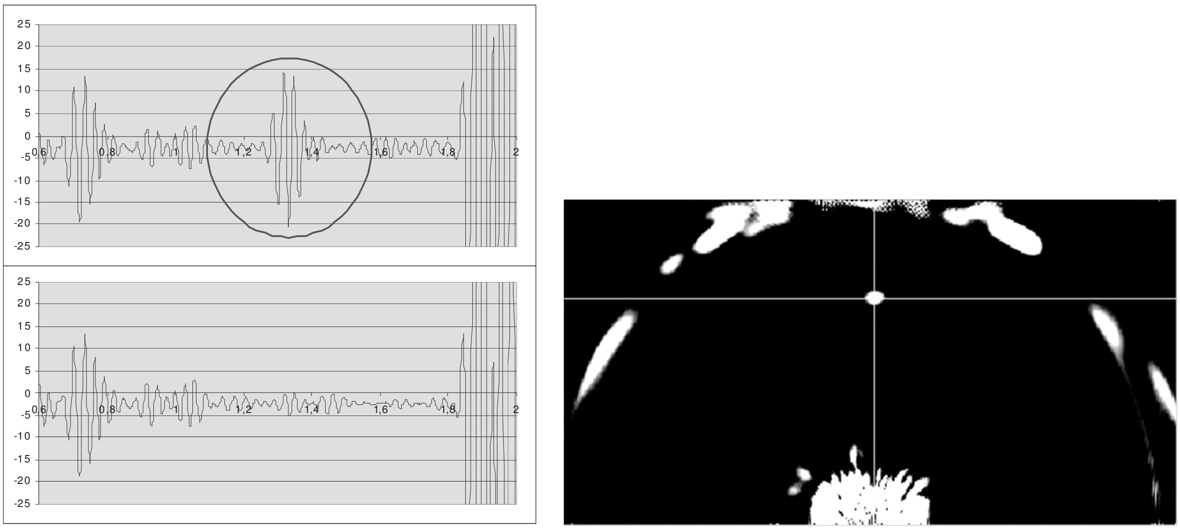


Figure 5 Left) Received waveform with pseudo-defect (top) and after removing the pseudo-defect (bottom). Right) 2D Plot obtained from phased-array data of the artificial notch applied at the same position. The signals around the bottom line and at the edge belong to corresponding reflections at the edges and the actuator array.

One should not assume that pseudo-defects, covering the same area such as real defects, cause almost identical reflections with respect to absolute parameters, such as the amplitude. One of the most important reasons is the limited acoustic contact between the sample and the pseudo-defect, even when both surfaces are firmly pressed against each other. The actual goal is to determine trends of how the incremental change of respective dimensional parameters are related to each other. This should lead to a library where clear assignments between the ultrasonic signals of real defects and its respective pseudo-defects are possible. The final goal is to establish a mapping for the probability of detection at different positions on an aluminium plate.

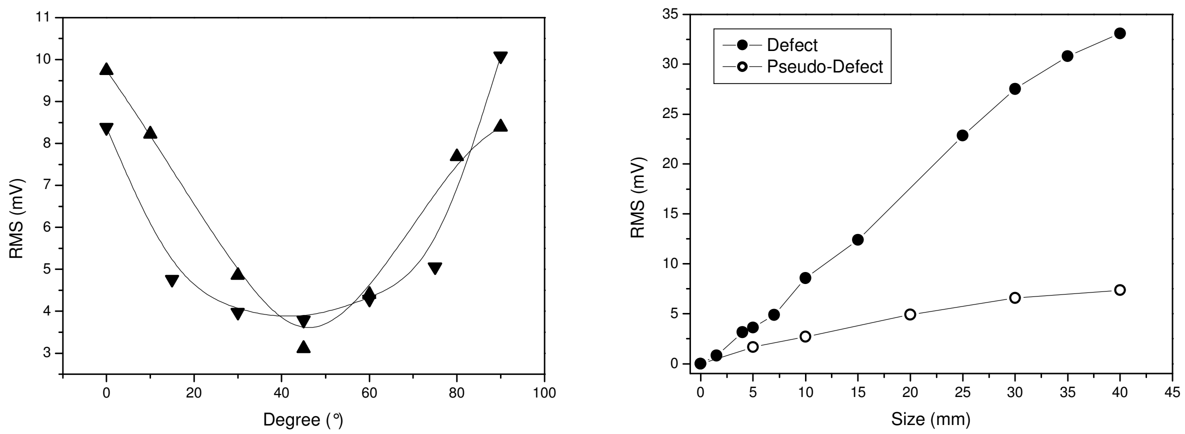


Figure 6 Left) RMS of waveform reflected at square-cut pseudo-defects as a function of the angle towards the wave front. The two curves represent slightly different positions with respect to the source. Right) RMS of waveforms reflected at pseudo-defects and artificial defects as a function of the length of the reflector being in line with the wave front.

The diverse results obtained with pseudo-defects are compared with the acoustic response obtained from real artificial defects (cut) applied by a dedicated tool (Figure 6).

The results obtained show that principal features between defects and pseudo-defects are similar, this regards the behaviour of "trends" such as the reflected amplitudes when the size of the pseudo-defects are changed systematically. Over all the reflector sizes investigated, the ratio between the RMS values is stable in the frame of the accuracy. Such as expected, the amplitude is systematically smaller, and the ratio depends on the absolute reflector size (Figure 7). That factor enables a given reflector size to roughly predict the RMS of a real defect when data of pseudo-defects were determined.

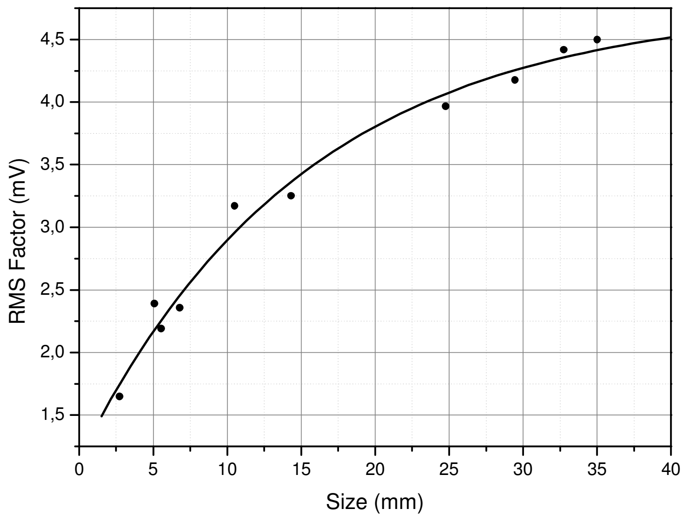


Figure 7 Possible nomogram for deriving a conversion factor for a given reflector size to roughly predict the RMS of a real defect when data of pseudo-defects were determined.

This is an encouraging result. Further research must confirm that the amplitude-relationships are stable and reproducible and the detailed behaviour of mode conversions will be studied. For this reason, an advanced facility for applying pseudo-defects is being established (Figure 8). In a final step, the application of pseudo-defects should be completely automated to enable a completely controlled validation process. A sufficiently large number of pseudo-defects will be used with different geometric symmetries results in a huge number of signals that will train the detection capabilities of the advanced data analysis tools of the respective SHM system for individual aircraft components.

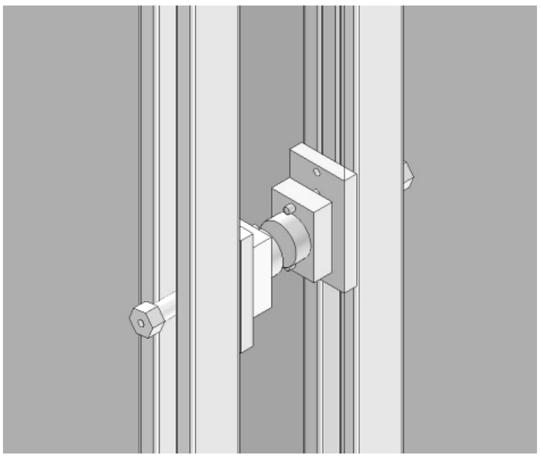


Figure 8 Facility to apply pseudo-defects.

The preliminary results clearly indicate that pseudo-defects have the potential to serve as a tool for the validation of defect detection systems in plate-like structures. It affects the same area such as real defects, providing similar variation of reflection and transmission. However the absolute magnitude of the corresponding mode conversion coefficients is different. But it is more interesting to see the trends of how the incremental change of respective dimensional parameters are related to each other. This should finally lead to a library where clear assignments between the ultrasonic signals of real defects and its respective pseudo-defects are possible. The final goal is to establish a mapping for the probability of detection at different positions.

ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n°212912 (Project: Aircraft Integrated Structural Health Assessment II - AISHA II).

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