Phased-array applications for aircraft maintenance: fastener-hole inspection

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ABSTRACT

In the aerospace industry, detecting the cracks that sometimes develop around fastener holes is a major issue for aircraft maintenance and life extension. Parts undergoing inspection are usually made of an aluminum alloy and typically have a complex geometry. Cracks of concern can be as small as 0.04 inches and can be located anywhere throughout the fastener thickness. The challenge is to design a technique that can be used from a single side, that does not require removal of the fastener, and that provides satisfactory resolution. The phased-array concept is to use a large linear array in a pseudo-tandem configuration, in which different elements of the same probe are used for transmission and reception. Excellent resolution is achieved using this technique, as shown in both simulation and experimental results.

INTRODUCTION AND DESCRIPTION OF THE PROBLEM

In the aerospace industry, detecting the cracks that sometimes develop around fastener holes is a major issue for aircraft maintenance and life extension. Parts undergoing inspection are usually made of an aluminum alloy and typically have a complex geometry (i.e., non-parallel interfaces, non-linear thickness variation, etc.). The focus of this article is on the fastener-hole region at the skin-spar junction, close to the fuselage, as illustrated in Figures 1 and 2. The spar thickness varies from 0.5 to 2 inches in the inspection area. Cracks of concern can be as small as 0.04 inches and can be located anywhere throughout the spar thickness.

The conventional eddy current (EC) inspection technique requires the fastener to be removed. The challenge in developing an easier and less expensive inspection strategy is to design a technique that can be used from the skin side, that does not require removal of the fastener, and that provides the same or better resolution than the conventional method. The most promising alternative was phased-array ultrasonic technique (PAUT). In contrast to conventional ultrasonic systems that use a single piezoelectric crystal, phased-array probes are composed of multiple elements that can be designed either as a general purpose transducer, or optimized for a specific application.

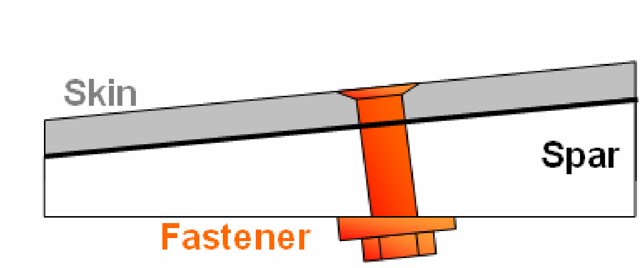

Figure 1: Structure undergoing inspection

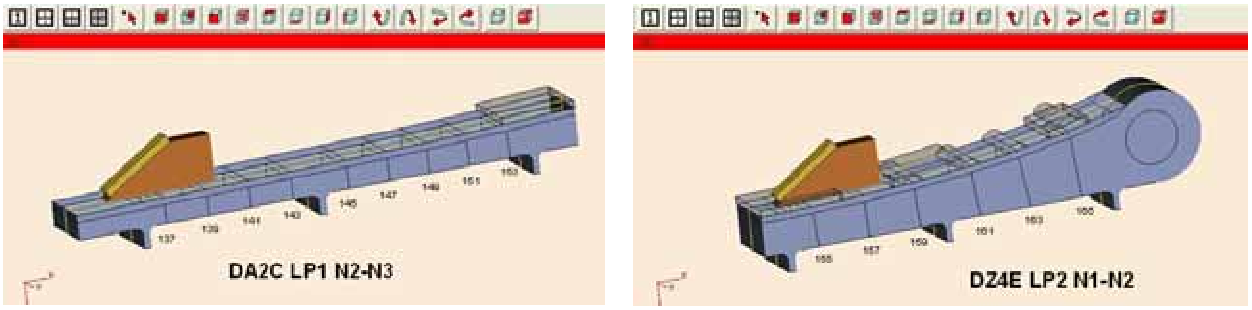

Figure 2: Typical geometry undergoing inspection: the structure is a two-layer part, consisting of a thin skin on top off a thick spar held together by a large number of fasteners. On the left, the spar thickness is representative of the middle of the wing structure. On the right, the spar thickness is greater closer the fuselage junction. On top of the skin, the fastener heads are indicated to illustrate access constraints.

The advantages of phased-array systems include improved resolution and flexibility derived from the ability to perform electronic focusing, beam steering and scanning. While the extensive capabilities of phased-array systems promise to improve inspectability and resolution for many nondestructive inspection applications [1, 2], they also make it more difficult for users to determine their probe and controller requirements. Modeling stands to be an increasingly important tool for both specifying hardware and for determining optimal inspection strategies.

DASSAULT AVIATION (business jet and jetfighter manufacturer) has been investigating a phased-array NDT procedure for fastener-hole inspection at the spar-skin junction. The concept is to use a large linear array in a pseudo tandem configuration, in which different elements of the same probe are used for transmission and reception [3]. In this article, the inspection principles are detailed before being simulated using CIVA software. Simulation computations are used to optimize the probe design as well as to illustrate the benefits of the phased-array inspection strategy. These results are then used to specify equipment and to perform experimental measurements on a real part containing artificial defects. The experimental results are presented in the last section of this article.

PRINCIPLE AND FEASIBILITY

The pseudo tandem concept is to use a large linear array with separate sub-sections used at transmitter and receiver [4, 5]. The transmission elements are phased to perform a focused sectorial after reflection off the bottom surface. The receiving elements are used to perform a direct-path focused sectorial scan. The convolution between transmitted and received signals defines the active focal spot for the measurements. The objective is to obtain coverage over the entire thickness of the part while keeping the size of the focal spot fairly constant.

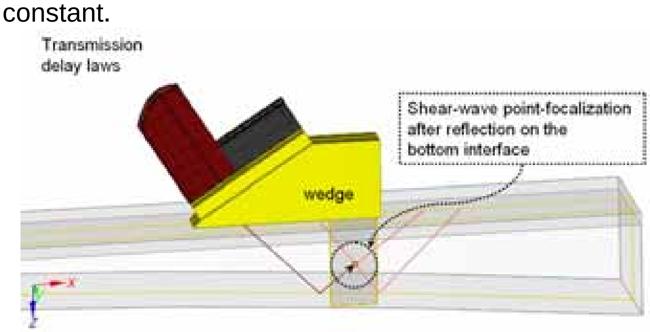

Figure 3: The lower part of the linear array is used for transmitting and focusing an ultrasonic shear wave at one point (orange disc) located in the spar. Focusing delay-laws are computed, accounting for reflection off of the bottom surface. Sound path and delay-laws are calculated using the actual CAD drawing of the spar.

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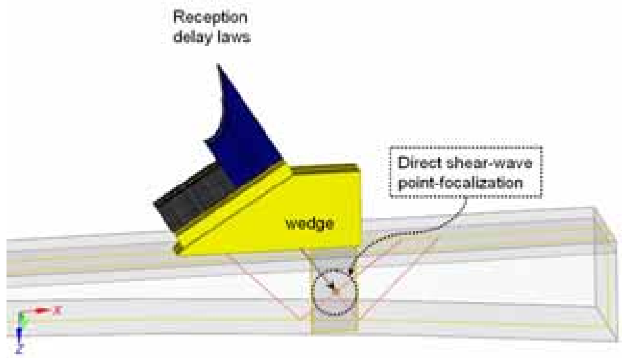

Figure 4: The upper part of the linear array is used for receiving and focusing an ultrasonic shear wave at one point (orange disc) located in the spar. Focusing delay laws are computed for a direct path to the desired location.

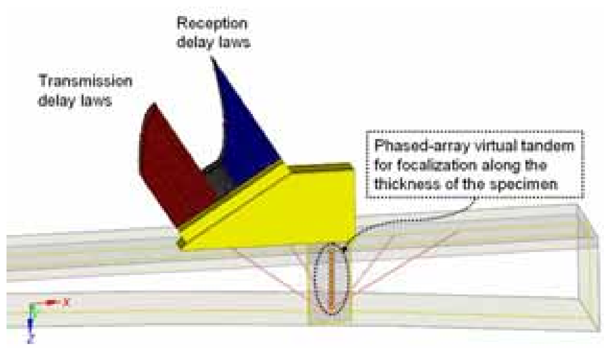

Figure 5: Repeating the delay laws displayed in Figures 2 and 3 for each focal point (orange disc) results in a focused beam throughout the entire thickness of the spar. The linear array will replace several focussed conventional tandem probes previously used (one for each depth).

This is achieved by using different elements for transmission and reception and by applying different delay laws to each set of elements. As illustrated in Figures 3, 4 and 5, transmitting elements are used to fire a shear wave focussed at one particular depth of the spar, along the fastener axis. Since a direct steering of the beam would result in side lobes that would affect the quality of the signals, the beam is instead focussed after reflection off of the bottom surface.

Accounting for the actual geometry of the spar, the delay-laws are computed so that the shear wave is focussed at the desired location (see Figure 3). For receiving the signals, the upper part of the probe is used to optimize the reception at the very same point targeted in transmission, this time for a direct sound path (see Figure 4).

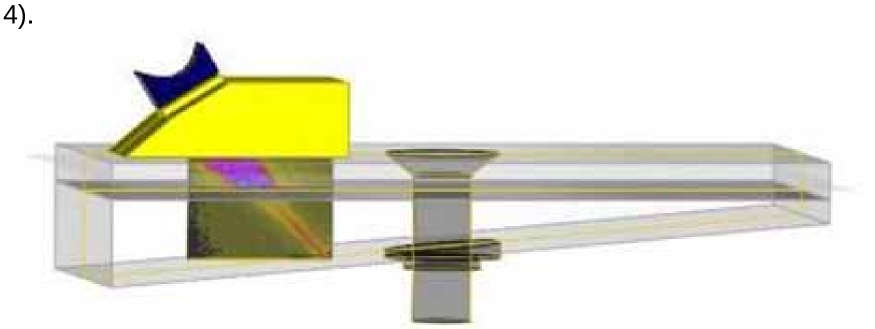

Figure 6: Beam simulation accounting for the sealant layer. Significant amplitude loss is predicted, and no noticeable beam deflection is observed. Correlated with measurements, the 3-layer problem is simplified into a single-layer problem for the NDT procedure optimization.

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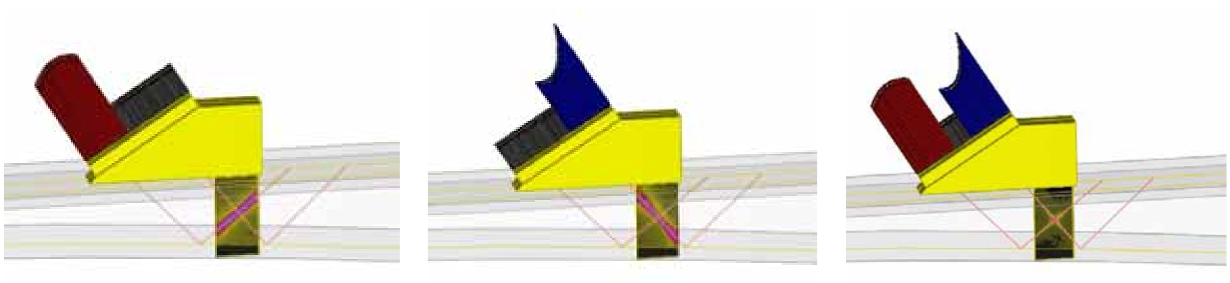
Using these two delay-laws in pitch-catch mode results in point focusing along the fastener axis. This process can be repeated automatically for every depth of the spar, thus providing consistent resolution throughout the entire length of the fastener (see Figure 5). This inspection strategy is simulated in the next section.

SIMULATION STUDY

Although it is not discussed in this paper, the problem of the interface layer between the skin and the spar has been studied at DASSAULT AVIATION. The feasibility of the measurements and the transmission coefficients have been evaluated with simulations and experimental measurements. It has been concluded that the problem can be decoupled into two parts: first the estimation of the transmitted beam into the spar, accounting for the ultrasound path through the sealant layer (see Figure 6), and second the NDT procedure optimization, knowing that no noticeable deflection is to be accounted for. In this article, the focus is on the inspection optimization.

The goal of the simulation study was to determine the best achievable array design to meet the detection requirements, given access and cost constraints. As seen in the experimental section, the space between fasteners is fairly narrow and the design has to account for the limited space. Calculations were performed using CIVA to evaluate the focal-spot size of several configurations, varying the number of elements, their shape and spacing, as well as the frequency. Snapshots of the acoustic beams are shown in Figure 7. The resulting focal spot is a sphere with a 3-mm radius that remains of constant size over the thickness of the structure under investigation. A 3D view of the convoluted beam is shown in Figure 8.

Results in terms of amplitude consistency are displayed in Figure 9. They show that measurements will remain in a narrow dynamic range for the whole spar thickness inspection. A set of simulations has made it possible to optimize the number of elements used in the procedure. Based on this study, the number of elements originally used for reception was found to be satisfactory. However, for transmission, the number of elements had to be increased to be able to focus over the full thickness of the part. The travel path to the focal spot is much greater when focusing after reflection off the bottom surface, and therefore requires a wider aperture to increase the penetration depth. Once the probe design was finalized, sensitivity studies were carried out to evaluate both the minimum detectable crack size and the coverage zone [4]. This was achieved by simulating the wave-defect interactions for several defect parameter variations, such as crack size, crack location and crack orientation. The results of this thorough simulation study are not discussed in this article, nor are the optimized probe design or detailed delay-law configurations. However results of the experimental measurements are presented in the next section, where the achievable resolution in terms of detection sensitivity is displayed.



(a) (b) (c)

Figure 7: Simulation results for a linear array used in a pseudo tandem configuration: (a) transmission, (b) reception, (c) Combined transmission and reception using the delay-laws displayed in figures (a) and (b) and the resulting effective focal spot. The convoluted beam shown is the intersection of the transmitted and received beams. A series of delay-laws is applied to make measurements throughout the thickness of the structure.

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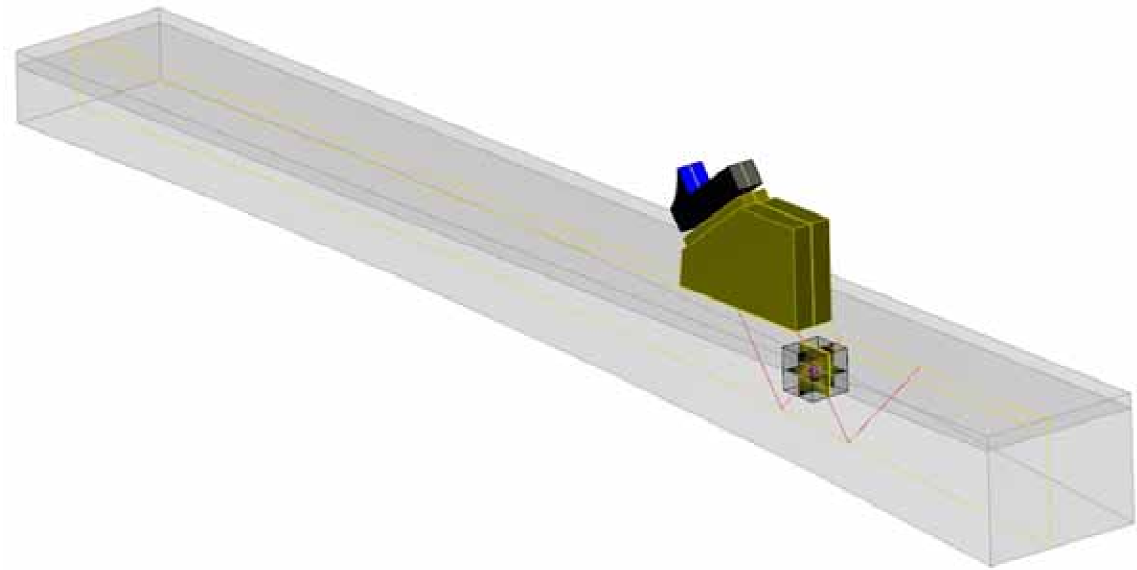

Figure 8: Simulation results from Figure 7c displayed in 3D in the CAD drawing of the test specimen. The solid lines indicate the ray paths of the shear waves, and the cube corresponds to the calculation zone.

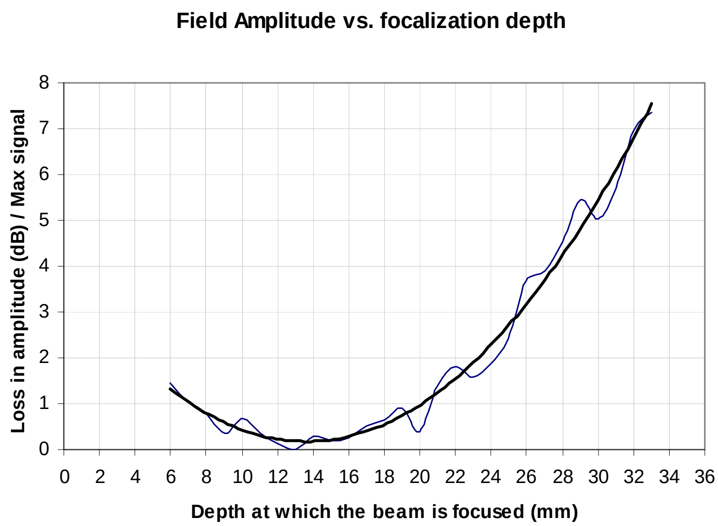

Figure 9: Beam amplitude-consistency through the thickness of the spar. The amplitude remains within a 10-dB range. This variation across the thickness has been reduced to 3dB by optimizing the number of elements used for focusing.

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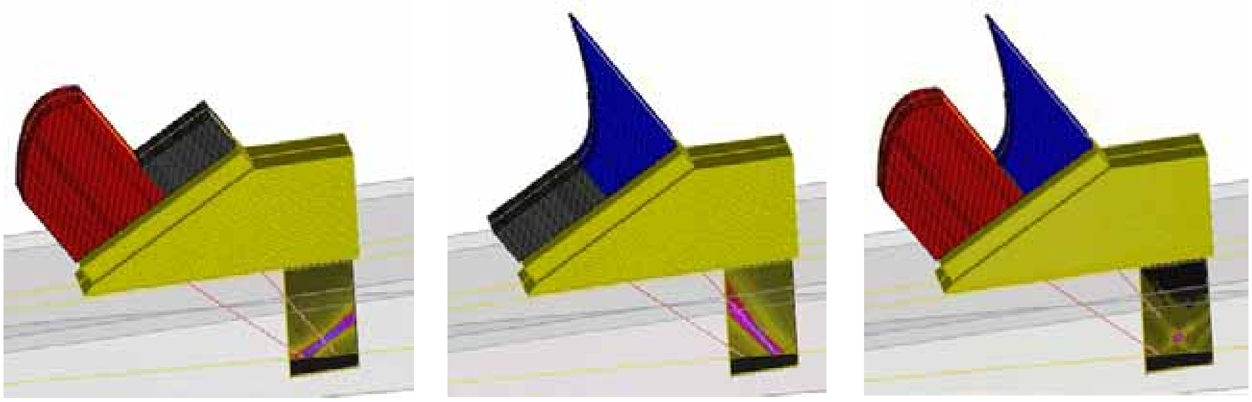

Figure 10: Another configuration for which the number of elements used in transmission is greater than that used for reception. The focal spot size is optimized as well as the consistency throughout the entire spar thickness; (a) Transmission, (b) Reception, (c) Combined transmission and reception using the delay-laws displayed in figures (a) and (b) and the resulting effective focal spot. The convoluted beam shown in (c) is the intersection of the transmitted and received beams.

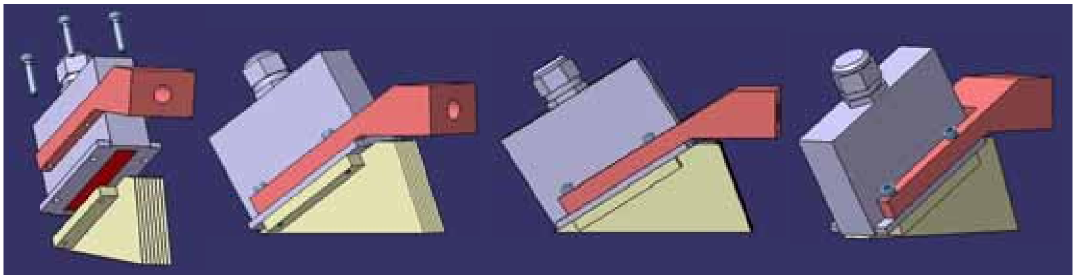

Figure 11: CAD drawing of the outside shape of the probe. Wedge and case dimensions are specified to ensure fit within the fastener heads. The external fixture device ensures precise probe positioning by the operator while performing the inspection. Courtesy of DASSAULT AVIATION.

EXPERIMENTAL VALIDATION: MEASUREMENTS ON ACTUAL PARTS

From industrial constraints compiled from the variety of geometrical models used on aircrafts, as well as from technicians' requests for ease of use, the ultrasonic phased-array probe has been optimized with simulation tools. Displayed in Figure 11 is the CAD drawing of the outside shape of the probe designed to fit between fasteners, as well as solve positioning issues raised by NDT inspectors. Experiments have been carried out on a real part, taken from a grounded jetfighter. Several sizes of EDM notches were created in several locations of the spar (see Figure 12). Measurements were performed using an M2M phased-array controller to drive the optimized probe.

The first step of the procedure is to obtain the image of the fastener hole. The axis of the probe is aligned with the fastener diameter. While the optimized focal laws are applied, the image of the fastener hole is displayed in the sectorial scan (see left picture in Figure 13). The echo visible in the scan is the reflection off the fastener hole in the spar. The probe is then moved laterally without rotating its scanning axis. The scan is now performed at the tangent to the fastener hole to detect the presence of cracks. When there are no defects over the thickness of the spar, no echoes are picked up by the scan and the image displayed on the live sectorial scan remains unchanged. When cracks are present, they act as reflectors and their echoes are picked up by the tandem inspection strategy. Thus, a crack located at half the thickness of the spar will produce the scan displayed in the middle picture in Figure 13. Another example of crack detection is given in the righthand picture in Figure 13. In this case the crack is located just underneath the skin in the spar.

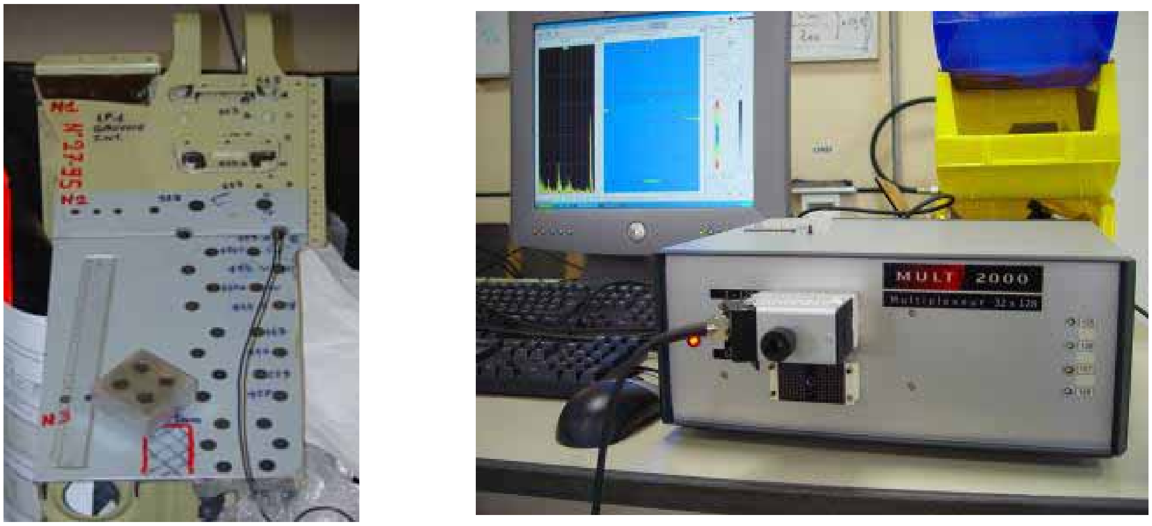

Figure 12: Photograph of spar undergoing inspection and experimental setup. Courtesy of DASSAULT AVIATION.

The sensitivity of the developed procedure is 0.5mm-crack detection at any depth of the spar. The inspection is flexible enough to cover a large range of thicknesses. Simulation helped to find a optimal compromise between the space between the transmitting and receiving parts of the probe and their apertures. The space between the transmission and the reception subsets of elements can be electronically controlled. The two subsets are set close together for thin-layers inspections and wide apart for thick zones. The size of both the transmitting and receiving subsets can also be adjusted for maximum resolution. For instance, since a larger aperture is needed for long sound paths, the active part used to focus after reflection off the bottom surface can be increased electronically. Knowing beforehand the geometries of the structures to be inspected, all the adapted configurations are loaded onto the phased-array system and applied automatically. This method has proven reliable and easy to use by inspectors. Their feedback is being taken into account to finalize the procedure and the visualization interface.

SUMMARY AND IMPROVEMENTS

The extensive capabilities of phased-array systems promise to improve inspectability and resolution for many nondestructive inspection applications. Studies at DASSAULT AVIATION demonstrate the advantages of phased arrays that include electronic focusing, scanning and beam steering, as well as real-time imaging. These features in turn enable inspection procedures that are faster, easier, and more reliable. Modeling stands to be an increasingly important tool for both specifying hardware and for determining optimal inspection strategies.

Simulations performed with CIVA software [5] illustrate how modeling is used to characterize the beam radiated into structures undergoing inspection, as well as the response of the radiated field to defects. This allows resolution limits and the minimum size of a detectable defect to be determined, as well as the coverage zone. Although phased-arrays and modeling do not eliminate the need for experimental validation, they can reduce the number of required tests. Moreover, both qualitative and quantitative characteristics of an NDT procedure can be evaluated using modeling tools such as CIVA. These modeling and parametric studies are often a necessary step in designing green-light/red-light solutions used in the field. Modeling also helps to find the optimal tradeoffs between performance and cost, while also meeting field constraints.

For the fastener-hole inspection challenge, simulations have been used to optimize the probe design in conjunction with the NDT strategy (choice of focal-laws to be applied). While applying the developed inspection, a relatively simple modus operandi ensures the detection of 0.5mm-cracks located anywhere in the spar thickness.

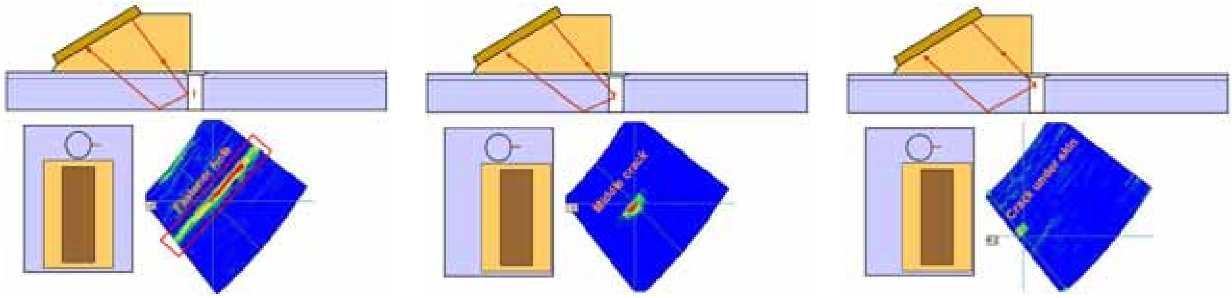

Figure 13: Experimental results. The left picture illustrates the echo off the fastener's vertical axis. The center picture shows the image of a middle crack. The right picture displays the image of a crack located underneath the skin. Courtesy of DASSAULT AVIATION.

For a better sizing ability and also to improve the ease of data interpretation, the fastener-hole echo should have the same amplitude from the top interface at the skin to the bottom surface at the spar. Using the latest development in the phased-array M2M electronics, shot-specific gain can be applied in order to ensure that the echoes off the fastener-hole are seen consistently throughout the thickness of the spar. Future plans call for implementing this feature to improve detection and sizing.

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5. More information is available at the following websites: www-civa.cea.fr, www.bercli.net, www.m2m-ndt.com.

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