FASTFOCUS™ PHASED ARRAY SYSTEM FOR AIR PLANE FASTENER INSPECTIONS

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Abstract: Phased Array ultrasonics was chosen as the inspection method to detect first-layer, faying surface fatigue cracks around fastener holes beneath the fastener heads, without removal of the fastener. A novel inspection technique for rapidly and reliably inspecting the area around fastener holes for cracks and corrosion has been developed *with no moving parts.*

The Phased Array design consists of a three-dimensional matrix of 504 ultrasonic elements on a cone that encircles the fastener head. Full circumferential scans are performed by programming the phased array focal laws to scan 360^o of the fastener holes, using a combination of the following scan patterns: pulse-echo at 45^o incident on the crack, pulse-echo at 90^o, plus local scanning. This capability allows flexible coverage of the fastener hole and surrounding area, again with no moving parts. Additionally, the beam deflection capability means that one probe is adaptable to a wide range of fastener diameters and skin thickness.

Numerical modeling along with experimental results was used to determine the optimal values for inner and outer radii of the cone, angle of the cone, number of elements and arrangement of the elements. Two complete prototype conical arrays were subsequently built.

The final portion of this project included developing the specific inspection procedures, and undertaking the Probability of Detection study (POD) developed by the FAA's Airworthiness Assurance Nondestructive Tested Validation Center at Sandia National Laboratory. The FastFOCUS program is now being expanded to other aircraft with thicker skins, and simulations of new arrays will be shown.

BACKGROUND

In the early 1980's, a fastener inspection system known as the Autoscan (see Figure 1) was designed and built to perform full circumferential scans around aircraft fasteners to search for faying surface corner fatigue cracks 0.030" and larger at the edge of fastener holes in the top layer of aircraft skin structures without removal of the fastener. It was designed to accommodate a variation in top layer skin thickness from 0.1" to 0.5" and in fastener hole diameter from 3/16" to 3/8". The unit used a pair of mechanically rotating ultrasonic probes for the inspection, and eddy current sensors to aid in centering the unit on the fastener.

Figure 1: Original Autoscan system

The Autoscan had reached obsolescence and was no longer maintainable, but the faying surface fastener inspections were still needed to ensure safety of the aging fleet.

The trade study revealed ultrasonics to be the method of choice.

Phased array approaches offered the possibility of reducing weight and size while increasing performance.

PHASED ARRAY ULTRASONICS

Phased arrays are an electronic method of generating and receiving ultrasound, which permits beam steering, beam scanning and beam focusing (see Figure 2). In a phased array, each element is individually wired to a pulser/ multiplexer and time delay circuitry. A selected series of these elements is fired with pre-determined delays to build up multiple wavefronts in the component.

The wavefronts interact, generating zones of constructive and destructive interference that yield the desired beam angle and focal spot position. By adjusting which elements are active and the set of time delays, the beams can be electronically steered and scanned to give complex inspection patterns. Using an array, *hundreds* of different conventional probes with varying angles and focal lengths can be simulated. An example of an angle beam formed from a linear array is shown below.

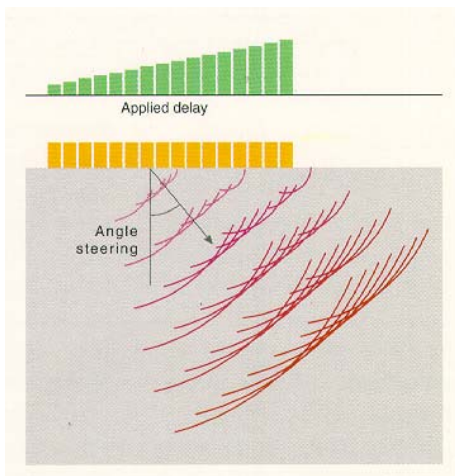

Figure 2: Forming an angle beam with a linear array

A NEW APPROACH

Using phased arrays, a novel inspection technique for rapidly and reliably inspecting the area around fastener holes for cracks was developed *with no moving parts.* Special probes using conical array of ultrasonic crystals have been designed for the aircraft fastener inspections. The probe developed is a three-dimensional conical array of ultrasonic elements laid out as shown in Figures 3 and 4.

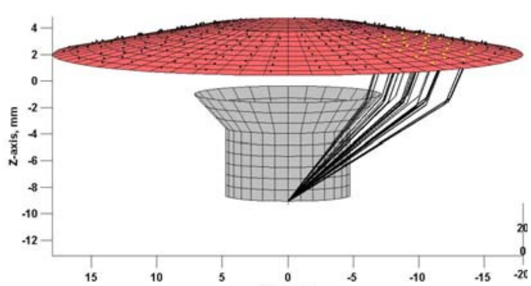

Figure 3: Probe side view with fastener

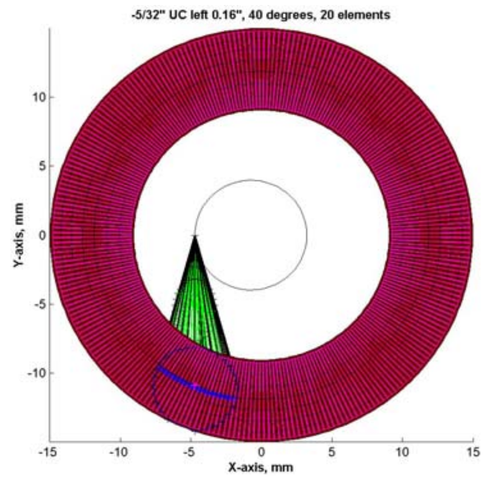

Figure 4: Probe Top View w/Fastener

FEASIBILITY STUDY

A Feasibility Study was initiated to determine if a practical probe could be produced reliably and economically. A primary concern was to minimize the presence of grating lobes. Grating lobes are known to appear when empty space exists between adjacent elements, and can generate misleading false signals if not sufficiently suppressed. To eliminate the empty space in the conical matrix design would have required over 4000 ultrasonic elements, which was neither technically feasible nor economical.

The challenge, from an ultrasonic point of view, was to select the largest elements possible that still have enough deflection power to generate the desired beams for all the desired fastener diameters and skin thicknesses, using the smallest number of elements possible while still maintaining acceptably low grating lobes. These elements will be distributed over a conical shape whose geometry must provide enough apertures to generate a 0.030" (0.75 mm) focal spot for all inspection scenarios.

The probe was designed using computer simulation to determine optimal values for:

- Number of elements
- Angle of cone
- Inner and outer radii of cone
- Size and shape of elements
- Waterpath

Computer modeling was used to simulate results for a set of sample cases representing extremes in the performance envelope. Each sample case included four sub-cases corresponding to the array being off-center by the centering tolerance towards the left, right, top and bottom (see Figure 5). For each focal law, the number of active elements required was determined. The shape and size of the probe was initially determined from the simulation results.

The modeled fields demonstrated that the array could be used to steer the focal spot to the all the desired depths and radial positions (see Figure 6). The fields also indicated the effect of the large inter-element spacing (primarily grating lobes). The goal was to keep the maximum grating lobes at 20 dB below or more below the amplitude of the focal spot. Known strategies to reduce peak grating lobe levels include randomizing the positions of the elements and minimizing the size of the cone further so that the elements are closer together.

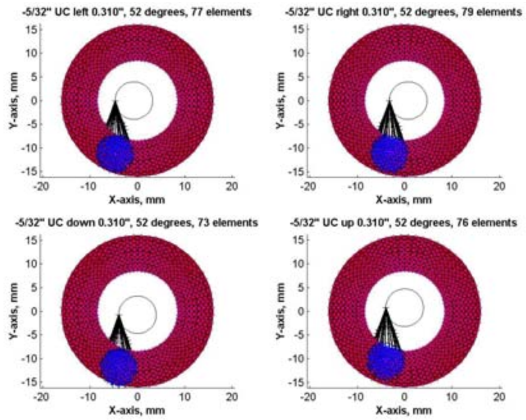

Figure 5: Computer simulation showing array off-center in four directions

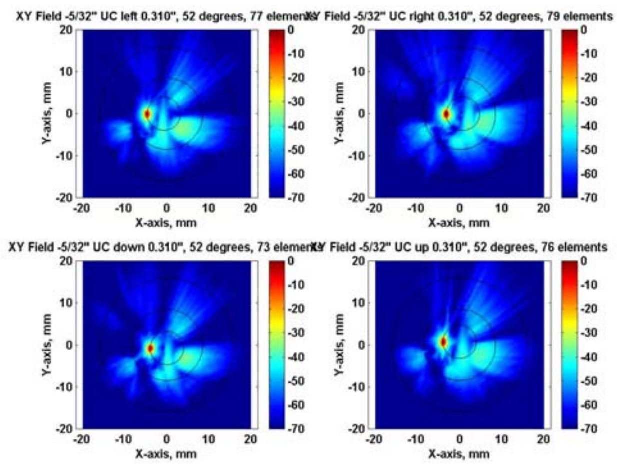

Figure 6: Simulated beam profiles

Several conical sub-arrays (Partial probes) were constructed to validate the design experimentally and to verify manufacturing feasibility.

The Feasibility results indicated that detection capability was high, potentially above the requirement of 0.030" on the first layer faying surface cracking (1-3).

PROTOTYPE PROBE DESIGN

The fastener inspection system uses a conical matrix array for centering and for scanning the fastener holes. The system consists of a 504-element array with instrumentation capable of addressing up to 512 possible elements with 64 multiplexed pulsers (see Figure 7).

This design permits three-dimensional beam deflection. The beam can be steered and focused to suit the fastener diameter and skin thickness variations. The 360^{o} array permits full coverage of the fastener without any probe motion. The scan around the fastener head takes place electronically through a rapid multiplexing operation. The frequency of the probe is 10 MHz. The current array design uses "quasi-random" element positioning to minimize grating lobes.

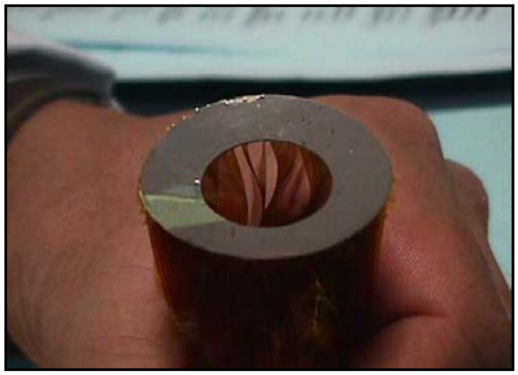

Figure 7: Prototype conical matrix array probe

Water Coupling

The coupling mechanism is a water filled membrane with small holes allowing water to seep through at the rate determined necessary. A photo of the disassembled coupling boot is shown below.

For centering, the operator will manually set the probe within +/- 0.060” (1.5 mm) of true center. Three hard rubber feet position the array the proper distance over the fastener head. This design permits inspection of protruding head fasteners as well as flush head fasteners.

Once centered within +/- 0.060” (1.5 mm) of true center, the system will aid the operator to center to within 0.030” (0.75 mm) . Once this centering accuracy is achieved, the system will:

- Indicate satisfactory positioning,
- Measure the hole location,
- Perform the scan.

Subsequently, the array will verify the position of the probe around the fastener to ensure that no probe movement occurred during the scan. The entire sequence is completed in a matter of seconds. The data will be displayed as a C-scan map with the fastener hole position indicated, and any defects shown in color; however in principle, almost any display is possible.

Probe Holder

Figure 8: Probe holder, known as the “hair dryer”

The phased array probe and water coupling is housed in a hard plastic holder similar in size and appearance to a hair dryer as shown in Figure 8. The encasement for the probe was designed to make it easily hand held.

Probe Holder Assembly

An electronics module is housed in the probe holder for local control functions. Switches are located at the rear of the housing assembly for initiating the centering assist process, initiating data collection, and accepting/storing data.

Instrumentation

The instrumentation is a customized FOCUS 64/512 phased array Quickscan developed by R/D Tech Inc. A photo of the instrumentation is shown in Figure 9.

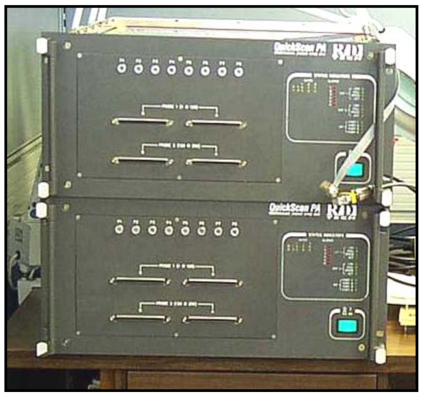

Figure 9: FOCUS 64/512 Quickscan

Prototype System

The first prototype of the FastFOCUS ultrasonic phased array system has been completed (see Figure 10). Typical Probability of Detection (POD) results are shown later. A test stand was constructed to hold the test specimens simulating the underside of an aircraft wing. A Heads-up-Display was included in the system to allow seeing the screen while under the wing (see Figure 11).

Figure 10: FASTFOCUS inspection in progress

Figure 11: Overhead inspection using the heads-up display

POD TEST RESULTS

Sandia National Laboratories carried out extensive POD testing, using all seven parameter sets and both notches and artificial fatigue cracks. A typical set of results is shown in Figure 12, for one of the better categories.

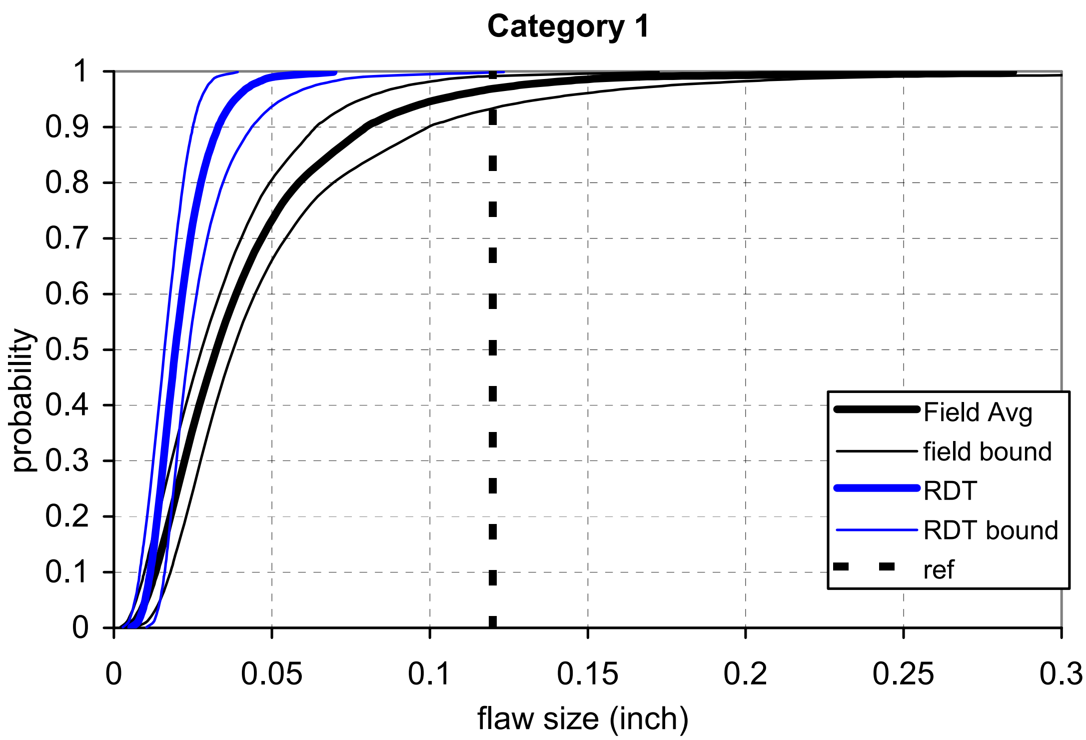

Figure 12: POD results from FastFOCUS trials, category 1

A number of comments can be made about these results. First, the R/D Tech operator performed better than the others to start, but this advantage disappeared with time and practice. Second, some categories were better than others, partly due to the inherent capabilities of the array. Third, notches were more detectable than cracks, as expected.

Summary: The objective of this project was to develop a lightweight, hand-held device for rapidly and reliably inspecting the area around fastener holes for faying surface cracks, standard shaft cracks and countersink cracks, without removal of the fastener.

Using phased arrays, a new inspection technique for rapidly and reliably inspecting the area around fastener holes for cracks has been developed *with no moving parts.* Special probes using conical array of ultrasonic crystals have been designed for the aircraft fastener inspections. A prototype probe with 504 elements was built, and integrated into a 64/512 Focus system. Further capability is currently being developed. This additional capability includes corrosion mapping, pitch-catch inspections, skin thickness measurements, detection of other defects such as exfoliation and shaft cracking. The final portion of this project includes developing specific inspection procedures and performing Probability of Detection (POD) tests to verify the capabilities.

References:

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2. P.G. Herzog, J.J. Selman and M.D.C. Moles, "Phased array FastFOCUS system", Aging Aircraft 2003, New Orleans, LA, USA, Sept 8-11, 2003.
3. P.G. Herzog, "Inspections of fastener holes using FastFOCUS ultrasonic phased array system", ASIP, Savannah, GA, USA, Dec 2-4, 2003.