AEROSPACE NDT USING PIEZOCERAMIC AIR-COUPLED TRANSDUCERS

D. K. Hsu[1], V. Kommareddy[2], D. J. Barnard[1], J. J. Peters[1]. and V. Dayal[3]
[1] Center for NDE, Iowa State University, Ames, Iowa, USA
[2] GE Global Research Center, Bangalore, India
[3] Department of Aerospace Engineering, Iowa State University, Ames, Iowa, USA

Abstract: In the nondestructive inspection of aerospace materials and structures, water-coupled ultrasonic inspection is often not desirable due to contamination and property alteration concerns. Examples include composite and foam structures in space applications and honeycomb sandwiches that cannot tolerate water ingression. For practical and operational reasons, water-coupled ultrasound is also not preferred for on-aircraft inspection in maintenance hangars. Non-contact, air-coupled ultrasonic transducers are therefore an attractive alternative for such applications. This paper describes our experience of using piezoceramic air-coupled transducers for flaw detection and repair evaluation of composite parts. The paper first discusses the basic principles of air-coupled ultrasonic measurement and laboratory tests of various materials and structures, followed by a description of a portable, manual, air-coupled ultrasonic scan system that allowed the use of air-coupled ultrasound in the field inspection of aircraft components.

Introduction: The goal of this work is to first gain experience of air-coupled ultrasonic testing (AC-UT) in the laboratory by applying the technique to a variety of composite and metallic structures, and then to develop a portable scanning system using commercially available components so that air-coupled ultrasonic testing can be applied in the field on aircraft structures. With this goal in mind, commercially available piezoelectric air-coupled ultrasonic transducers and the associated pulser and receiver [1] were acquired for conducting the laboratory experiments and for incorporating into a portable scanning system. The considerations used for making the choice were mainly the penetrating power of the system and the compactness and robustness for field applications. The laboratory investigation for AC-UT consisted of transducer field profile mapping for planar and focused probes, quantitative measurement of the transmission insertion loss of air-coupled ultrasound in various solids, and imaging of defects and flaws in composite and metallic structures using a conventional laboratory immersion ultrasonic scanning system with the immersion tank removed. The effort of developing a portable system for field use of AC-UT has concentrated on the adaptation of a commercially available magnetically coupled wireless position and orientation tracker [2] as a position encoding device, the fabrication of a light weight yoke fixture for AC-UT transducers, and the development of a data acquisition and analysis software. The fieldable AC-UT system has been completed and initial on-aircraft tests have produced good results.

NDE Using Air-Coupled Ultrasound: Ultrasonic testing (UT) is one of the mature modalities of nondestructive inspection for aerospace structures. Contact mode UT typically uses oil or gel as a couplant and is applied manually using portable flaw detecting instrument. Water-coupled ultrasonic inspection are widely used by OEM in manufacturing where large aerospace parts are scanned in automated squirter systems [3]. Ultrasonic inspection by immersion or squirter systems cannot be conveniently applied in the field, although closed-cycle, water-coupled systems have been developed for field use [4]. Air-coupled ultrasonic inspection has the distinct advantage of being couplant-free, but also suffers from several significant disadvantages. The primary limitation of air-coupled ultrasound are the large reflection loss at the air-solid interface [5] and the large attenuation of high frequency ultrasound in air [6]. The latter has limited the application of AC-UT to frequencies mainly below 1 MHz or so. In the NDE of aerospace structures, where internal flaws and defects are to be detected and imaged, the current state of AC-UT technology is mainly on transmission mode inspection that requires two-sided access. The piezoelectric air-coupled ultrasonic transducers used in this work are planar or focused narrow-band probes with center frequencies of 120 kHz or 400 kHz; purchased from QMI, Inc. [1] These transducers are driven by their matching electronics, the SONDA 007CX pulser and receiver system. The dimensions of the piezoceramic elements of the QMI air-coupled transducers range from 3/4" to 1" diameter and the focal length is typically 1" to 2". Figure 2 shows a photo of the transducers and a representative field profile of a 400 kHz, 1" diameter transducer with a focal length of 2 inches. The focal spot size (FWHM) of this transducer is about 1/10 inches. The beam profile images are obtained using a planar transducer of the same center frequency and apodized to a small aperture of 1/32 inches diameter as a point receiver.

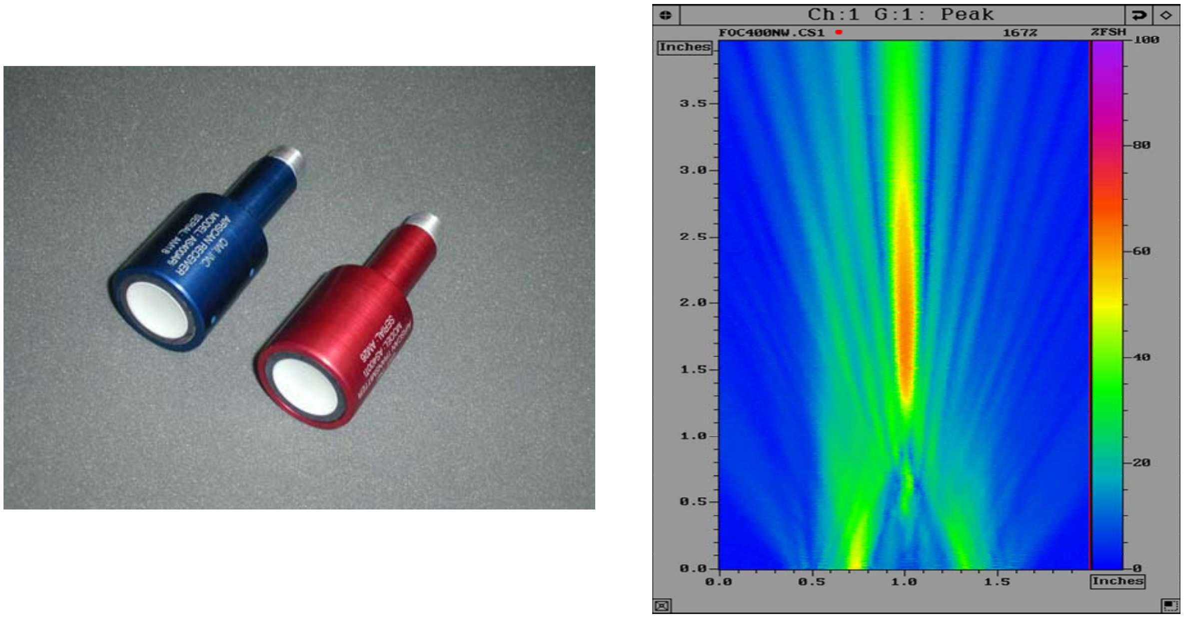

Fig. 1 Piezoceramic air-coupled transducers and field profile of a focused probe.

The QMI air-coupled UT system uses a toneburst excitation on the transmitting transducer and has a built-in low noise preamplifier in the receiver transducer. The received signal is typically a sinusoidal wave train of approximately 40 to 80 μs. The FFT frequency spectrum of a 120 kHz time domain signal shows that the 6dB bandwidth is approximately ±10% of the center frequency.

Penetration Power of Air-Coupled Ultrasound: When air-coupled ultrasound is used in the NDE of aerospace materials and components, a deciding factor for the successful application is the penetrating power of the waves. The orders of magnitude difference between the acoustic impedance of air (420 Rayl) and that of structural materials (17 MRayl for aluminum and 4.8 MRayl for CFRP) is the fundamental cause for the highly inefficient transmission of air-coupled ultrasound through solid materials. Based on the classical formula of transmission coefficient through a material of acoustic impedance Z_2 surrounded by a material of acoustic impedance Z_1,

$$T = 4Z_1Z_2 / (Z_1 + Z_2)^2, \qquad (1)$$

the insertion loss would be approximately 80 dB for aluminum and 70 dB for CFRP in air. For a solid plate of finite thickness d, the transmission coefficient [7] is given by:

$$T = \frac{1}{\sqrt{\left(1 + \frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2\left(\frac{2\pi f d}{c}\right)\right)}} \qquad (2)$$

where $m = Z_2/Z_1$, f is the frequency, and c is the velocity of sound in the plate. Since the air-coupled ultrasound used in this work is a finite-duration toneburst with a bandwidth of approximately ±10% of the center frequency, the transmission coefficient is modified by the frequency spectrum $S_i(f)$ of the incident wave. The time-domain signal transmitted through the solid plate of thickness d should therefore be given by the following inverse Fourier transform :

$$S_t(t,d) = \int_0^{\infty} \frac{S_i(f)e^{i2\pi ft}}{\sqrt{\left(1+\frac{1}{4}\left(m-\frac{1}{m}\right)^2 \sin^2\left(\frac{2\pi fd}{c}\right)\right)}} df \quad (3)$$

Experimental results of air-coupled ultrasonic amplitude transmitted through thin plates of CFRP and aluminum are compared with the calculated values in Fig. 2 for a toneburst centered at 120 kHz [8]. As the thickness of the plate increases, the transmitted signal amplitude drops rapidly and asymptotically approaches the value predicted by the classical formula in Eq. (1). The resonance peaks in the transmission coefficient associated with the sine squared term in the denominator are not observable in the experiments due to low signal-to-noise ratio. It should be pointed out that since the interfacial losses at the air-solid and solid-air interfaces far outweigh the attenuation loss in the material at the low frequencies used in AC-UT, it is much more difficult to transmit through two thin plates than to transmit through one thick plate. Delaminations in CFRP laminates, even in 1.5"-thick filament-wound rocket cases, can be mapped out by transmission C-scans of air-coupled ultrasound.

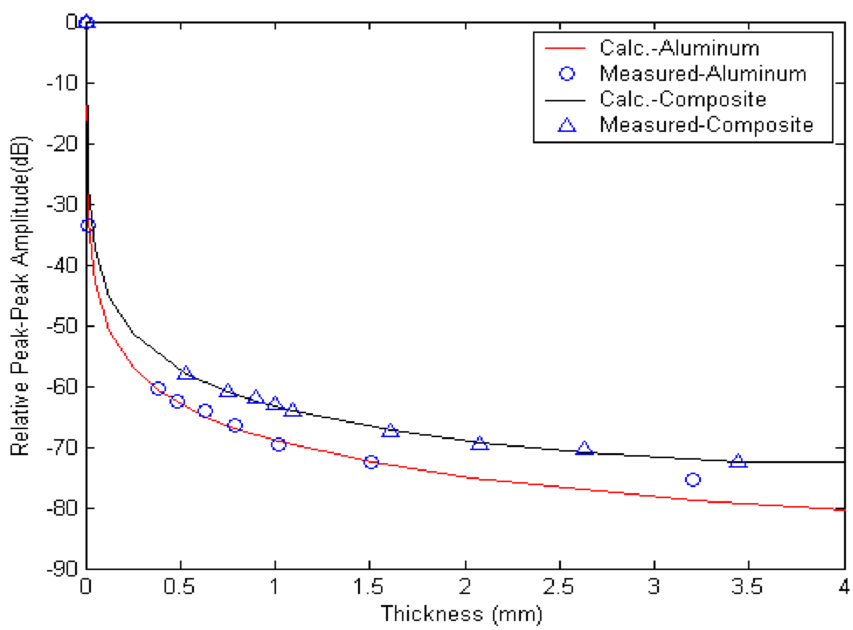

Fig. 2 Comparison of measured and calculated signal transmission of a 120 kHz toneburst.

Through Transmission Air-Coupled Ultrasonic C-Scan: The most effective mode for applying air-coupled UT in the nondestructive inspection of aerospace structures, just like water-coupled ultrasound, is still scanning and imaging. The implementation of through-transmission C-scan using AC-UT is not difficult and can be easily achieved using most conventional ultrasonic scanners. In thin CFRP laminates delamination flaws can be detected and imaged in transmission C-scans. The smallest detectable flaw size depends on the frequency, the transducer size and the focusing condition. With focused ultrasonic beam at 400 kHz, it is generally not difficult for AC-UT to detect flaws of 1/8" diameter. Figure 3 shows an example of AC-UT image of Teflon films embedded in a 10-ply CFRP laminate [9].

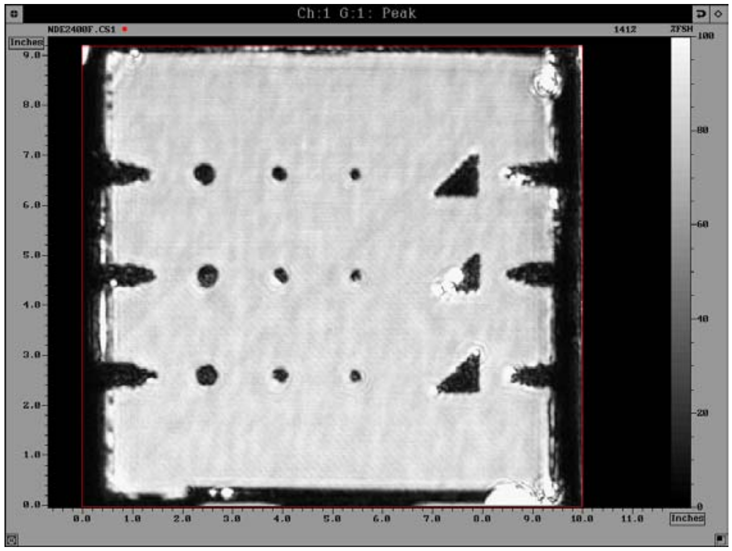

Fig. 3 Air-coupled transmission ultrasonic image of flaws in a 10-ply CFRP.

A considerable fraction of composite components and control surfaces on aircraft are honeycomb sandwiches. Air-coupled ultrasound can readily transmit through such honeycomb structures. As described in the last section, very little sound energy can be transmitted through two facesheets separated by air. Practically all the energy transmitted through a honeycomb sandwich has propagated along the cell walls of the honeycomb core. This does not seem to hamper the ability for AC-UT to image disbonds between the facesheet and the core or defects within the facesheets. Figure 4 shows six disbond defects in an aluminum honeycomb sandwich with 0.032" facesheets and 3/8" cells. The image is obtained with focused 120 kHz air-coupled, 3/4" diameter transducers.

Air-coupled ultrasonic scanning has been used in nondestructive imaging of composite honeycomb sandwiches and repairs on such structures. Transmission C-scan is highly effective for mapping out the extent of core damage caused by impacts that may or may not be visible on the surface. Figure 5 shows the lateral extent of crushed core of a visible impact damage and the internal damage of a non-visual impact damage. The size of the impact induced core crush revealed by the image in Fig. 5(a) is about three times larger than the diameter of the visible dent on the surface. The specimen containing the non-visual impact has been cut in half to reveal the core crush inside. The size of the semi-circular damage zone imaged by AC-UT is in good agreement with the actual extent of the core fracture.

Repairs made on CFRP honeycomb sandwiches can also be evaluated with AC-UT scans. The scan image can reveal the size of the core replacement, the presence and continuity of core potting, and defects such as delaminations in the repaired facesheet or disbonds between the skin and core [10].

Development of Portable Air-Coupled Ultrasonic Scanner: To apply air-coupled ultrasonic inspection in the field for nondestructive imaging of aircraft control surfaces, a scanning device is needed to acquire the transmitted signal amplitude as a function of transducer position. Unlike the situation in a laboratory, existing scanning systems designed for water-coupled ultrasonic inspection cannot be readily adapted for conducting air-coupled through-transmission ultrasonic testing. An effort was therefore made to develop a portable, manual scanner for AC-UT. The decision to build a manual scanner rather than a mechanized one was made based on considerations of scanner weight, cost, portability and ease of use. A lightweight yoke for holding the probes was built from commercially available carbon composite tubes and solid laminates [11]. The position information was provided by a magnetic encoding system known as the Flock-of-Birds (FOB) [2]. It is a general purpose motion tracker that

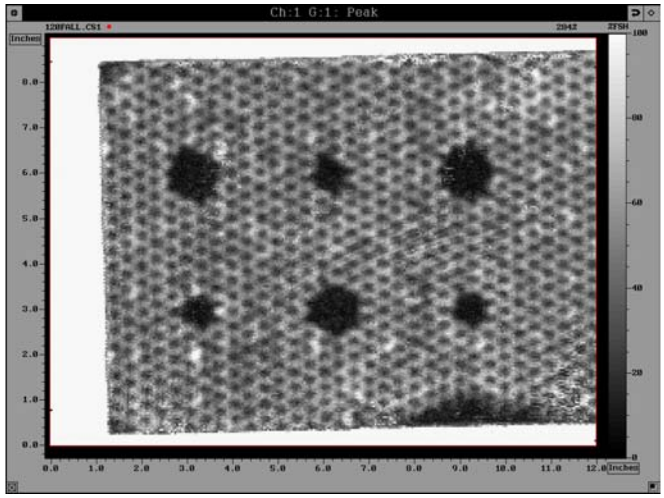

Fig. 4 Disbonds in aluminum honeycomb sandwich revealed by AC-UT transmission C-scan.

(a)

(b)

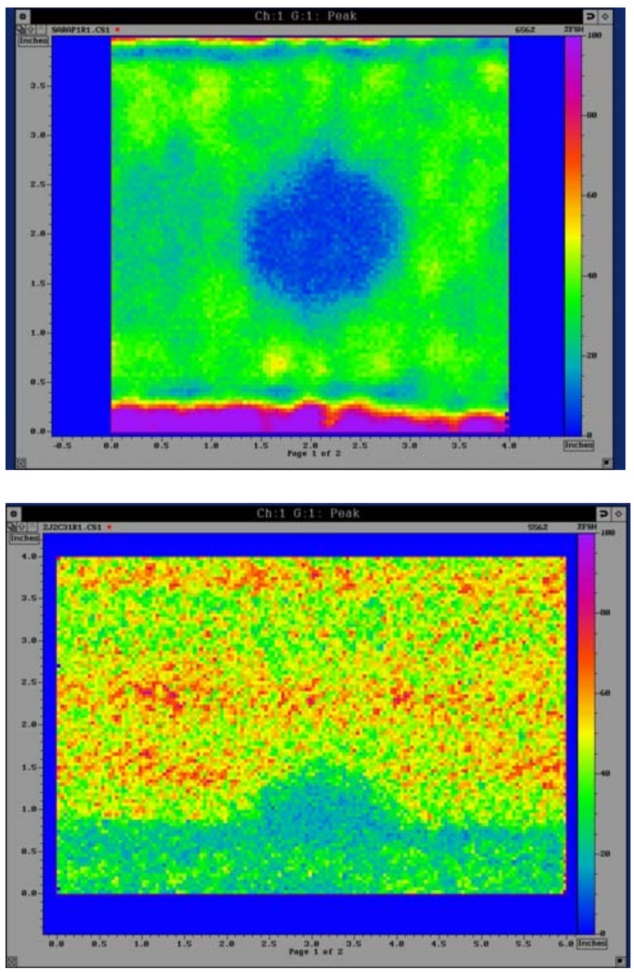

Fig. 5 Air-coupled ultrasonic transmission C-scan of a visible impact damage (a) and one-half of a nonvisible impact damage (b).

provides the position and angular orientation of a receiving sensor with respect to a stationary transmitting antenna. The receiving sensor of the FOB is mounted on the transducer yoke, but not necessarily near the transducers. The transmitting antenna is located within about 60 inches (range of the FOB) of the receiving sensor. Software was written to use a laptop PC for controlling the data acquisition when the yoke is scanned by hand to cover a selected scan area. The position data from the FOB enter the PC via a serial port, and the peak amplitude of the transmitted signal within a specified time gate was taken from the QMI SONDA and fed into the PC after going through a simple A/D converter. The ultrasonic data and the position data are then combined to produce the C-scan image. A schematic diagram of the system is shown in Fig. 6. Defects in aerospace structures such as delamination or disbond usually appear as regions of low transmission amplitude in the C-scan image; however, some defect images may contain a region of increased amplitude due to diffraction and interference effects that are prevalent at lower frequencies [9].

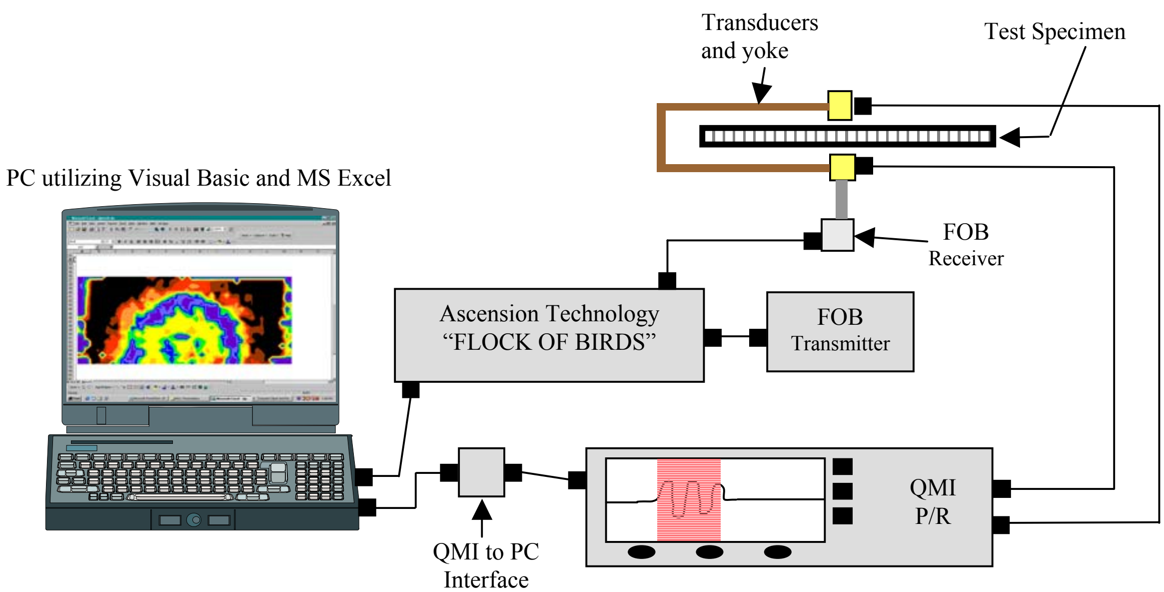

Fig. 6 Schematic diagram of the manual air-coupled ultrasonic scanning system

One of the drawbacks of imaging by manual scan is that it can be slow and tedious when the transducers are moved in a random fashion to completely cover a scan area. A small pixel representing the transducer position and its sampling area must be moved around to cover the entire area of scan. A more efficient approach is to first fill the scan area quickly with a larger pixel size and then "zoom in" on indications of suspect regions with smaller and smaller pixel to refine the flaw definition. The initial pixel size should be chosen based on the spread of the transducer beam profile and the detection sensitivity so that a flaw will not escape detection even though its image is of low resolution. Finer scans of only the selected regions using smaller pixels will then provide more accurate flaw size, shape, and severity information. The advantage of this approach is that the resolution change can be made on the fly during the scan and that the implementation only requires some software development. Figure 7 shows a manual C-scan image of three flaws in a honeycomb test panel taken with different resolution in various regions of the image. This technique has been shown in field tests to save scanning time without sacrificing the probability of detection.

The manual air-coupled ultrasonic scanner has been tested in the field on aircraft components in maintenance hangars. The hand-scanned AC-UT unit was found to produce good scan images of defects and damages in composite and aluminum honeycomb structures. Figure 8 shows a scan image acquired on a damaged Black Hawk helicopter rotor blade. The image, obtained using the resolution change on the fly feature, revealed core crushes in the tangential direction caused by a tree strike. These appeared as two dark horizontal features

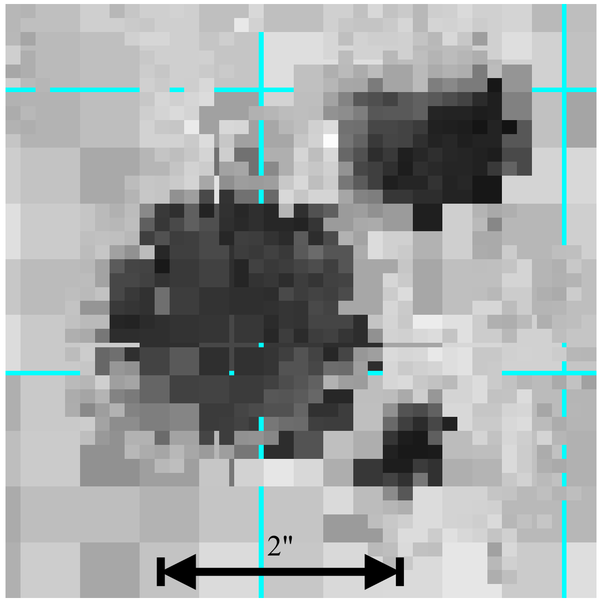

Fig. 7 Images of flaws obtained with the "resolution change on-the-fly" feature.

in the image of Fig. 8. The image also showed a bright feature in the near-vertical direction that was attributed to the normal honeycomb-to spar transition in the rotorblade.

Conclusions: Air-coupled ultrasonic NDE of aerospace structures using piezoceramic transducers has been successfully carried out both in the laboratory and in the field on aircraft components. Capabilities and limitations of the AC-UT system were first investigated in the laboratory using quantitative measurements, followed by the development of a fieldable manual scanning system based on commercially available air-coupled ultrasonic equipment and position encoding instrument. The ability of changing scan resolution on the fly has made manual scanning more practical. Initial field test results are encouraging but further testing will undoubtedly lead to more modification and improvement of the system.

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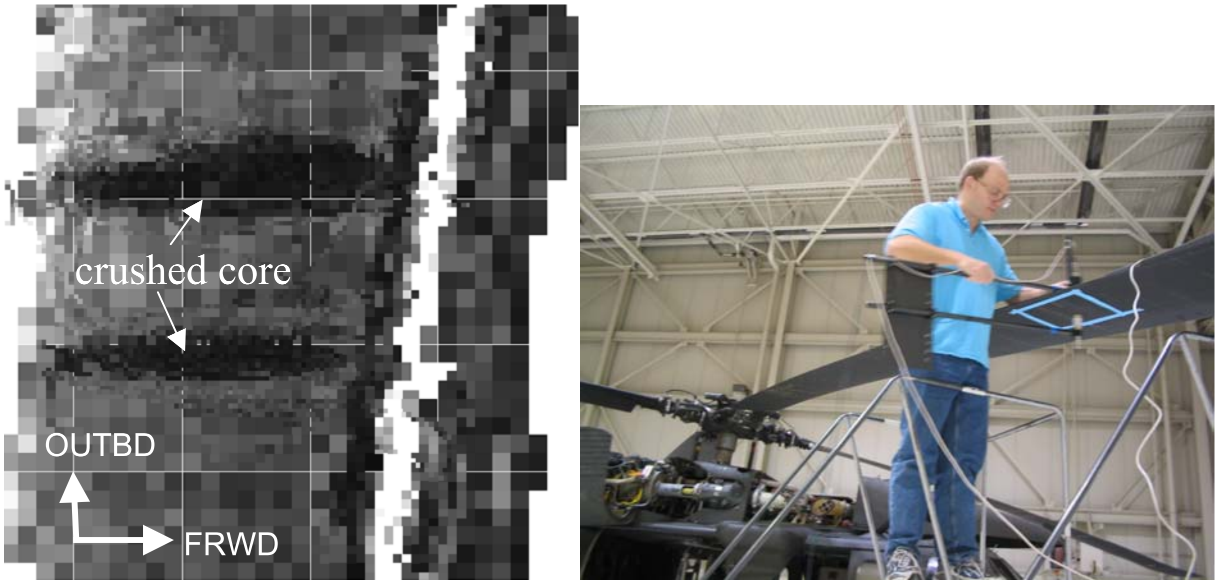

Fig. 8 Damages of a helicopter rotorblade as imaged by the manual AC-UT scanner.

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