USE OF PHASED ARRAY ULTRASONICS IN AEROSPACE ENGINE COMPONENT INSPECTIONS: TRANSITION FROM CONVENTIONAL TRANSDUCERS

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Abstract: The University of Dayton Research Institute (UDRI), under contract by the US Air Force, has designed and constructed a fully automated ultrasonic inspection system for the detection of embedded defects in rotating gas turbine engine components. The automated inspection system, designed and developed under the Turbine Engine Sustainment Initiative (TESI), makes use of phased array ultrasonic technology for increased throughput and detection capability. Current inspection requirements for aerospace applications, however, are based on the use of conventional transducers and time honored methodologies. The implementation of phased array technology into existing routine ultrasonic inspections requires a reinterpretation of inspection procedures and results from conventional transducers. This paper will discuss current progress in a study conducted to directly compare ultrasonic setups for phased array and conventional transducers. The inspection results obtained from both conventional and phased array systems under several setup conditions will be presented.

Introduction: The use of ultrasonic inspections for the detection of hidden defects has been used extensively throughout the aerospace industry for structures, pre-production and serviced engine components, as well as material processing quality control [1,2]. Procedures for the use of conventional single element transducers for the inspection of pre-production and serviced engine components are well established, and the processes are routine for many components. Many of these procedures were developed based on antiquated electronic devices however, and have not been updated to reflect changes in ultrasonic technology over the years. Implementation of newer technology that provides increased detection capability, as well as data storage and processing opportunities, will allow for improvements in reliability and efficiency of the inspection process. These technologies will require new approaches to embedded defect inspections and necessary changes to the time honored techniques that are commonly employed. The challenge to the inspection developer is to incorporate the new technology into the inspection process, without any degradation in coverage or sensitivity from that under which the original inspection procedures were developed.

Under the Turbine Engine Sustainment Initiative (TESI), the University of Dayton Research Institute (UDRI) has designed and constructed a fully automated ultrasonic inspection system for the detection of embedded defects in rotating gas turbine engine components. The TESI inspection system makes use of advanced technologies in many areas, including: probe positioning (robotics), part recognition (vision systems) and automated scan plan execution (software) [3]. Improvements in ultrasonic inspection capability and efficiency are provided in the system by the incorporation of phased array ultrasound technology. Use of the phased-array ultrasonic instrument and probes allows for optimization of both the sensitivity and resolution for each inspection through electronic beam-steering, scanning, and focusing processes. However, direct implementation of phased array transducers into existing inspection procedures developed for conventional transducers is not straightforward. Specifications for conventional probe acceptance and qualification are not applicable to multidimensional array probes and must be rewritten accordingly. Similarly, routine surface focusing procedures commonly used with single element probes are inappropriate for array transducers. The focusing and steering conditions used in an inspection can be optimized for the specific component geometry and inspection requirements, since there are many possible probe configurations that simply achieve the same focal depth. Characterization of the beam profile for each possible probe configuration is not possible, or practical for a routine setup. However characterization of the beam profile throughout the interrogation volume is required for developing an inspection procedure that ensures coverage and sensitivity throughout the inspection. Therefore, standardized processes for characterizing the beam requirements and focusing conditions for array transducers are needed, but have not yet been developed.

Under the TESI program inspection procedures are being developed for engine disk bore geometries, which include many flat surfaces. These relatively simple geometries allow for the efficient use of the linear array transducers for much of the inspection. Currently, 5 and 10 MHz linear array transducers are being characterized for use in the disk inspections. Since creation of the focused beam relies on refraction at the water/material interface, proper characterization of the array transducer beam profile must be performed using reflectors inside a specimen, preferably of the same material. Characterization blocks which contain closely spaced side drilled hole (SDH) and flat bottom hole (FBH) targets from 0.125-3.0 in. depth have been designed and produced by UDRI for beam profile measurements. In order to insure that the beam profile and performance of the array transducer compares closely with that of the specified conventional transducers currently being used, the beam profiles of both transducers have been characterized in the same way, and the results compared. The following discussion will focus on the characterization of a 10 MHz, 64 element (0.45 X 5.0 mm element size) linear array transducer (R/D Tech Ultrasound Transducers, 60 Decibel Rd., State College PA) and a 10 MHz, 3" focus, 0.375" diameter single element transducer, (UTX, Inc. 112 Milltown Road, Holmes, New York).

Results: The experimental setup used in this study consists of the R/D Tech Tomoscan III pulser/receiver and Tomoview 2.2R9 software for both data acquisition and hardware control for all inspections using both the linear array and conventional single element transducer. The gantry x-y scanning system provided transducer positioning with a scan and index resolution of 0.5mm. For the linear array transducer, electronic scanning in the index direction was combined with mechanical stepping, where needed, to acquire data over the entire inspection volume.

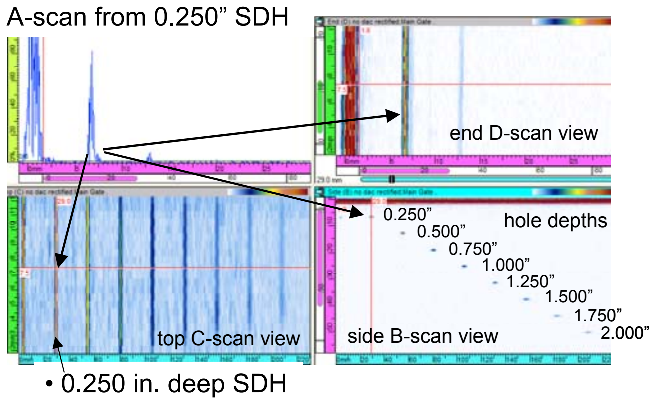
Characterization of the ultrasonic beam was performed using a Rene 95 calibration block which contained 0.020 inch diameter SDH's located at 0.125, 0.250, 0.500, 0.750, 1.00, 1.250, 1.500, 1.750 and 2.000 inches depth. The use of SDH targets allows for characterization of the ultrasonic beam in both a normal incidence or shear beam configuration, however this paper will discuss only normal incidence beam characterization. The beam width for an unfocused transducer 0.375 inches in diameter would be roughly 0.094 inches, while the wavelength of sound in Rene 95 at 10 MHz is 0.024 inches. Thus, the 0.020 inch SDH is small enough to properly characterize the beam width, but is also large enough to be easily detected by the 10 MHz wave. Both transducers were aligned so that the active area was parallel to the top surface of the characterization block. Further details of the setup configuration used for each transducer are described below.

All inspections conducted using the conventional single element transducer used a 3.0 in. water path. This probe configuration is commonly used for aerospace embedded defect inspections. Placing the focal point of the transducer at the part surface also serves to optimize the inspection for the near surface sensitivity. Sensitivity deeper in the part is obtained with the use of a depth (or time) amplitude correction (DAC). Typically, reflections from side drilled hole (SDH) or flat bottom hole (FBH) targets at various depths are used to determine the gain values for the DAC curve. Although focusing the transducer at the surface of the part does not make efficient use of the transducer focusing power over the inspection volume, surface focusing does allow for the use of a simple linear depth gain correction.

Use of a linear array transducer provides the flexibility to focus the beam optimally within the part. However, focusing at many different depths is not necessarily required for all inspections. Design of an efficient ultrasonic inspection process will optimize both sensitivity and inspection speed by minimizing the number and complexity of the focal laws used. In the current study, the primary inspection volume is roughly 2.0 inches in depth. Therefore, the array transducer was set up to focus at 3 different points within this volume, 5 mm, 19 mm and 35 mm. The optimum focal law will be obtained by a comparison of the array beam profiles for each focusing depth, with that of the conventional transducer.

Discussion: In order to compare the beam profiles from both transducers, the same setup procedure was used for each. Typical inspection requirements for embedded defects specify that the transducer gains be set to achieve an 80% full scale height (FSH) peak amplitude from a target located at a particular depth. For the current study, the SDH located at 0.250 inches was used as the setup target. The setup process was performed manually, and the instrument gains adjusted to achieve a minimum peak amplitude of 80% FSH from the SDH. The transducer was then scanned across the entire SDH block and the A-scan and C-scan data recorded. The C-scan data obtained with the conventional transducer shows visually that the peak amplitude of the reflection decreases with depth (Figure 1). Analysis of the C-scan results included peak amplitudes and –6dB beam width for each of the SDHs. A plot of peak amplitude versus SDH depth was used to determine beam attenuation, while the –6 dB beam width was used as a measure of beam spreading. Table 1 lists the peak amplitudes and –6 dB beam widths for the conventional transducer. The data show that the amplitude of the SDH reflection does decrease as expected with depth in the part, but there is a significant spreading of the beam diameter with increasing depth also.

Application of a DAC which incorporates increasing gain with depth can correct for beam attenuation, but will not compensate for beam spreading. In effect, the wider beam at larger depths amounts to over sampling as well as a decrease in detection resolution. The effect of beam spreading is particularly apparent when viewing the B-scan in Figure 1b. The B-scan view shows the cross section of the characterization block through each of the holes. The tightly focused beam shows the SDH as a small circular feature near the top of the block, but the deeper holes become progressively more spread out.



(a) (b)

Figure 1. Beam profile characterization for a 10MHz conventional transducer. (a) A-scan reflection from 0.020” SDH and top view C-scan from ultrasonic beam profile characterization block. (b) simulated side and end views of the block cross-section created from A-scan data.

Table 1.
Beam Profile Analysis-Conventional Transducer

SDH depth (mm)	conventional transducer (33.0 dB total gain)	
	peak reflection amplitude/ peak noise amplitude	-6 dB beam width (mm)
3.2	90/2	2.0
6.4	86/2	2.5
12.7	62/2	2.5
19.0	47/2	2.5
25.4	32/2	3.0
31.8	24/2	4.0
38.1	19/2	4.0
44.4	17/2	4.0
50.8	9/2	5.5

Beam profile characterization for the linear array transducer was conducted using the same basic procedure as for the conventional probe but with appropriate modifications for the array transducer geometry. Due to the variable focusing capability of the linear array, water path can be selected somewhat independent of the focal depth. Therefore, a 25 mm water path was selected which provides sufficient water path for efficient focal law creation, but also minimizes the variability that can result from the use of a long water path. Another difference between the linear array transducers and conventional spherical focused transducer is the presence of a non-focused beam direction. The conventional transducer is focused to a cylindrically symmetric spot by design. However, without the use of a curved array or lens, the 1-dimensional linear array is inherently a line-focused transducer. Therefore, beam profile characterization of a linear array transducer must be performed for both probe directions. Figure 2 shows schematically the orientation of the array probe relative to the SDH targets and the resulting beam focusing direction. The figure also illustrates that interrogating an asymmetric target, such as a SDH, with an asymmetric beam, such as the line focus from a linear array, the beam area that intersects the target is different for each orientation. Thus, the gain settings required to achieve an 80% FSH reflection from the SDH are expected to also be different for each orientation. This paper will discuss characterization of the beam profile for both probe orientations. The orientation shown in Figure 2a with the focusing direction of the probe parallel to the SDH long axis will be referred to in this text as the lateral scanning mode. The probe orientation shown in Figure 2b, with the probe rotated 90 degrees from that shown in 2a, will be referred to as the normal scanning mode. Lateral scanning mode will be discussed first.

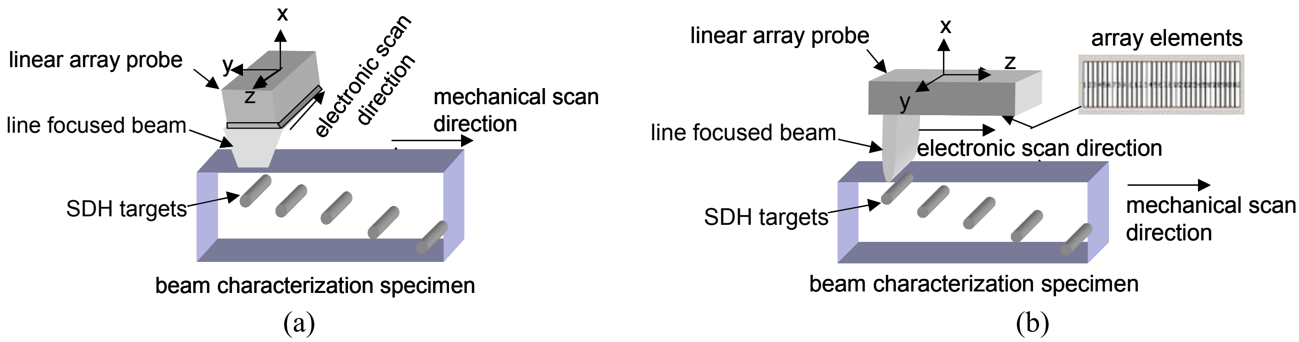
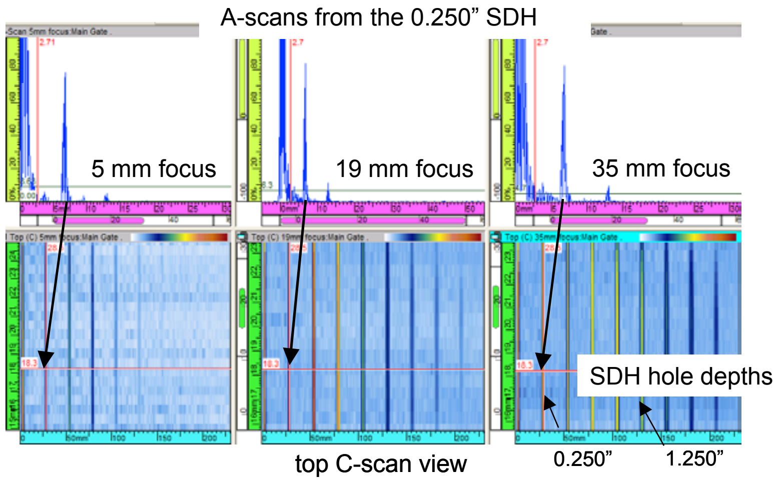


Figure 2. Linear array transducer orientation relative to the SDH characterization block. (a) transducer oriented with the active (focusing) direction parallel to the SDH axis (beam width ≈ element length) (b) transducer oriented with the focusing direction perpendicular to the SDH axis.

As mentioned above, the linear array was used with 3 different focusing configurations, or focal laws. For array transducers, selecting a focal distance inside the component does not uniquely define the probe configuration. For the current study, the number of elements selected for generating the focused beam was based on an appropriate aperture for that particular focal depth. For example, focusing at 5mm depth in Rene 95 with a 25 mm water path, corresponds to an aperture whose near field distance in the part would be approximately 5 mm in diameter (or 11 elements wide). Similarly, focusing at 19 and 35 mm depth corresponded to an aperture of approximately 8 and 10 mm in diameter (16 and 20 elements) respectively. Using a different number of elements for each focused beam also implies that a different gain setting will be required for each focal law in order to achieve the 80% FSH peak amplitude for the reflection from a 0.250” deep SDH. The total gain setting for each probe configuration is also reported since for inspections of ultrasonically noisy material the gain settings required directly effect detectability of a target.

Alignment and setup of the linear array was performed manually. Instrument gains were adjusted individually for each of the 3 focal laws to achieve a minimum peak amplitude of 80% FSH reflection from the 0.250” deep SDH. A-scan and C-scan data were recorded for each focal law simultaneously during the scan. For the lateral scanning probe orientation shown in Figure 2a, the transducer was mechanically scanned across the entire SDH block while electronically indexing across the probe to acquire the volume of data.

The C-scan data is shown with an A-scan from the 0.250” deep SDH in Figure 3. Similar to the conventional transducer, focusing the linear array near the surface of the part resulted in a continuously decreasing peak amplitude with depth. The gain setting for the array transducer focused at 5 mm (21 dB) was somewhat lower than that required for the conventional probe (33 dB). In contrast to the inspection results obtained with the conventional transducer, the amplitude of the SDH reflections increases then decreases with depth for the 19 and 35 mm focused beams. Figure 3 shows that focusing deeper in the part allows for better sensitivity with a lower gain setting than was possible with the conventional transducer. These results are directly related to the added benefits of beam focusing with the linear array. Table 2 lists the peak amplitudes for each focal law. Although subsurface focusing allows for better sensitivity inside the part, the effect of beam attenuation still results in an overall decrease in reflected amplitude with depth. The peak amplitudes for all 3 focal laws are shown together with those obtained using the conventional transducer in Figure 4a for comparison. The close correlation between the amplitudes obtained by focusing the array probe at 5 mm and the amplitudes obtained with the conventional transducer indicates that it is possible to approximate the conventional transducer response over the inspection volume with the lateral probe orientation. However, the figure also shows that the response of the array transducer can realize a significant increase in sensitivity by carefully choosing the subsurface focusing depth.



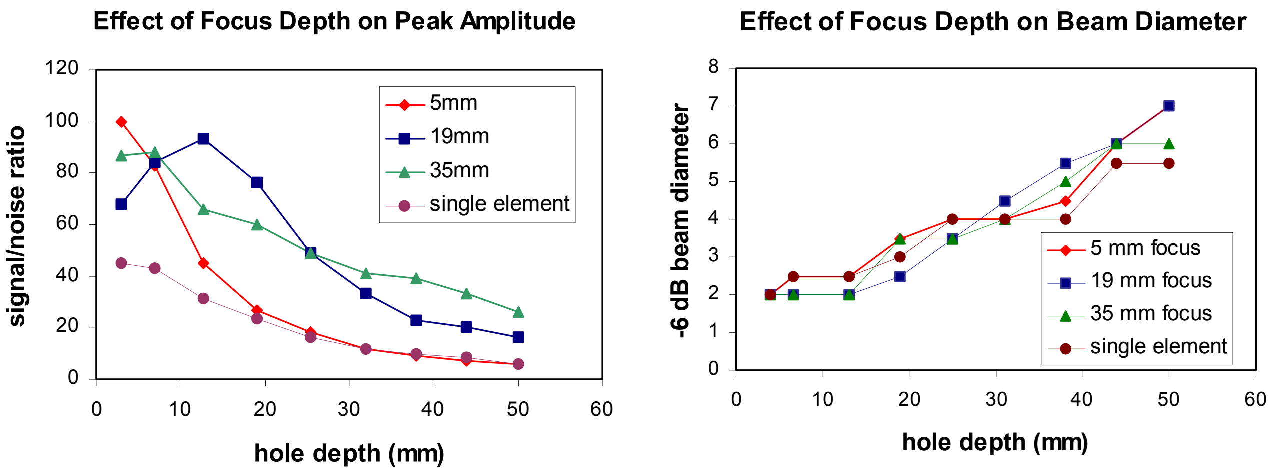
(a) (b) (c)

Figure 3. Representative A-scan from 0.250" deep SDH and C-scan images of entire SDH transducer characterization block. Scans were conducted using the linear array in the lateral scanning orientation with the active focusing direction parallel to the SDH axis. Focus depths: (a) 5mm (b) 19mm (c) 35 mm.

Table 2.
Beam profile analysis-linear array transducer lateral scanning mode

SDH Depth (mm)	single element	linear array--line focus		
	33.0 dB	21 dB	23.5 dB	24 dB
	peak signal/ peak noise	peak signal/peak noise (focus @ 5mm)	peak signal/noise (focus @ 19 mm)	peak signal/noise (focus @ 35mm)
3.2	90/2	100/1	68/1	87/1
6.4	86/2	83/1	84/1	88/1
12.7	62/2	45/1	93/1	66/1
19.0	47/2	27/1	76/1	60/1
25.4	32/2	18/1	49/1	49/1
31.8	24/2	12/1	33/1	41/1
38.1	19/2	9/1	23/1	39/1
44.4	17/2	7/1	20/1	33/1
50.8	9/2	6/1	16/1	26/1

Although the peak amplitudes show the effect of linear array focusing, the beam width measurements are independent of focal law (Figure 4b). Beam width for the lateral probe orientation is controlled by the element width in the non-focusing direction. For the probe in the current study the width in the passive direction is 5 mm. For an unfocused transducer of the same diameter, the natural focusing that occurs would result in a beam diameter at the near field distance of roughly 1.5 mm. The results shown in figure 4b show that near the surface of the characterization block the beam diameter does in fact correlate with the expected beam diameter of an unfocused transducer 5 mm in diameter. The data show that the variation in beam diameter with depth is nearly the same for each focal law, and is also very close to that observed for the single element transducer.



(a) (b)

Figure 4 Comparison between a lateral oriented linear array and conventional transducer response to SDH targets: (a) Variation in peak amplitude with SDH depth. (b) variation in –6 dB beam diameter.

Although the previous discussion demonstrated the advantages of focusing on sensitivity, the lateral probe orientation did not interrogate the beam in the actively focused direction. In order to examine the effects of focusing in the active direction the characterization block was scanned again with the probe in the normal scanning orientation (Figure 2b). The peak reflected amplitudes from the SDHs and –6 dB beam widths obtained are listed in the table below. This probe orientation clearly shows the effects of focusing on the peak amplitude and beam width. For each focal law, maximum amplitude and minimum beam width are obtained in the region near the beam focal point. It should be noted that saturation of the peak reflected amplitude near 20 mm depth resulted in an overestimate of the beam width for the 35mm focused beam. The beam characterization results for the normal probe scanning orientation is compared with that of the single element transducer in Figure 5.

Table 3.
Beam profile analysis-linear array transducer normal scanning mode

SDH Depth (mm)	focus @ 5mm 23.5 dB		focus @ 19 mm 28.0 dB		focus @ 35mm 32.5 dB	
	peak signal /peak noise	-6 dB beam width (mm)	peak signal /peak noise	-6 dB beam width (mm)	peak signal /peak noise	-6 dB beam width (mm)
3.2	100/1	1.5	70/	3.0	70/1	6.0
6.4	83/1	1.5	85/1	2.5	84/1	4.5
12.7	30/1	2.5	100/1	2.0	93/1	3.5
19.0	17/1	3.5	70/1	2.5	100/1	3.5
25.4	10/1	5.0	40/1	2.5	100/1	3.5
31.8	7/1	5.0	25/1	3.5	78/1	2.5
38.1	<5%		10/1	4.0	32/1	3.0

44.4	--		10/1	4.5	30/1	3.5
50	--		7/1	7.0	25/1	4.0

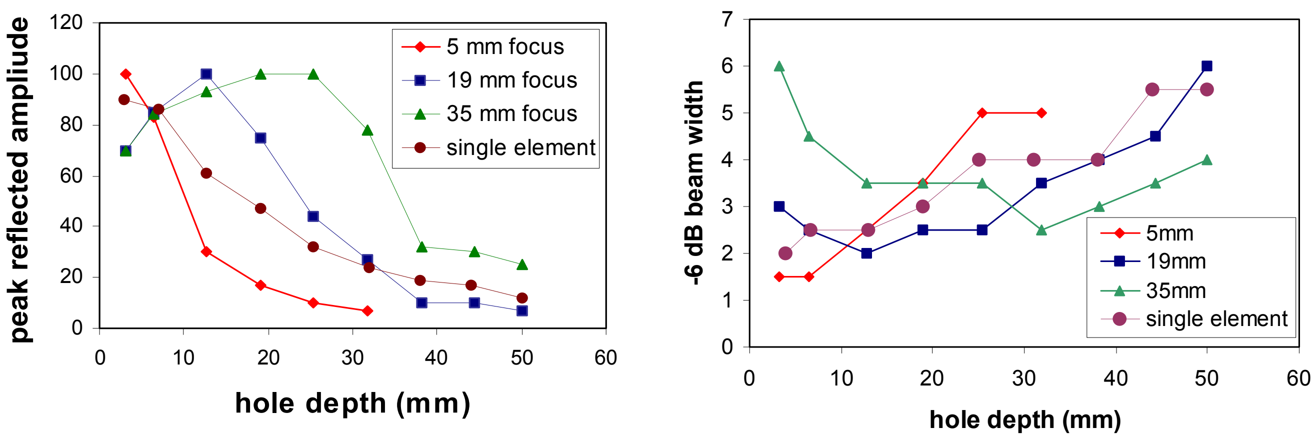


Figure 5 Comparison between a normal orientation linear array and conventional transducer response to SDH targets: (a) Variation in peak amplitude with SDH depth. (b) variation in –6 dB beam diameter. .

The variation in peak reflected amplitude shows that focusing the array probe inside the part results in an improvement in detection sensitivity. However, the variation in amplitude throughout the depth using a subsurface focus does not decrease continuously away from the surface of the block. Creation of an appropriate DAC curve to insure uniform sensitivity throughout the inspection volume must take into account the beam profile inside the part. As a result of the nonlinear amplitude variation, subsurface focusing will require a nonlinear DAC, where the number of points needed to define the curve will be focal law and inspected material dependent. Figure 5b shows that for depths greater than 6.4 mm, a smaller beam width, and thus better resolution, was obtained for subsurface focusing with the array transducer than the single element. Measurements of peak amplitude and beam width show that surface focusing of the array transducer does not simulate the beam profile of a surface focused single element transducer when using a normal scanning orientation of the array probe.

Conclusions: Under the Turbine Engine Sustainment Initiative (TESI), phased array inspection technology is being implemented into an automated inspection system for detection of embedded defects in turbine engine disks. Full implementation of phased array technology requires that current inspection requirements and procedures developed for conventional single element probes be redefined for phased array probes. Studies conducted to characterize the beam profile for the array transducer showed that subsurface focusing with the array transducer can provide equivalent sensitivity and resolution to that obtained with a comparable single element conventional transducer. For some array probe configurations, the sensitivity and resolution were shown to be improved over that of the conventional transducer. However, measurements of reflected peak amplitude from side drilled hole targets showed that the amplitude of the subsurface focused beam generated by the linear array does not decrease continuously with depth in the inspected part. This non-uniformly decreasing beam amplitude would require a non-linear depth amplitude correction to insure constant sensitivity throughout the inspection volume. Measurements of beam width for the array transducer showed that the beam width in the non-focusing direction of the linear array is comparable to that of the single element transducer. In the active focusing direction, the beam width varied with depth, approaching the theoretical limit near the focal point, and spreading away from the focal depth. Depending on the particular inspection requirements, optimization of the array focusing conditions to obtain the required resolution and sensitivity over the inspection volume may require use of multiple focal laws. Further studies are required to determine the focusing behavior of transducers with other geometries, under normal incident and angle beam configurations within a specimen, and how that behavior compares to conventional transducers.

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