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Abstract
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Keywords
data acquisition, acoustic arrays, acoustic noise, aperture antennas, nondestructive evaluation, QNDE

Disciplines
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Comments
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PHASED ARRAY TRANSDUCER FOR BILLET INSPECTION

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ABSTRACT. A phased array transducer design for billet inspection is presented. The transducer sweeps a uniform focus in both depth and angle to assure uniform coverage of the billet volume, particularly at the billet center, where coverage depends critically on transducer alignment. Design concepts are presented which enable the transducer to sweep a tight focus in both depth and angle using 63 discrete time delays. Design concepts and specifications are summarized, and experimental verification of design performance is presented. Data acquisition protocols are discussed enabling the phased array inspection to operate at production speeds.

Keywords: Ultrasonics, Billet Inspection, Phased Array
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INTRODUCTION

Past work funded by the FAA Engine Titanium Consortium (ETC) established that the signal-to-noise of defects embedded in a noisy titanium microstructure can be improved by decreasing the volume of the probing ultrasonic pulse, through increasing beam focus and pulse bandwidth.[1] This follows from the observation that, as the pulse volume decreases, the signal from a defect will increase more rapidly than signals scattered by neighboring microstructure. Using this principal, an inspection can be engineered to provide a specified defect signal-to-noise by maintaining a specified beam focus and bandwidth throughout the volume to be inspected. Maintaining a uniform focus throughout the inspection volume (uniform focus inspection) challenges conventional inspection practices which use either non-focused beams or beams focused at a fixed depth. One successful implementation of the uniform focus inspection uses multiple focused transducers ganged together, each focused at a different depth, so that the entire depth of a volume is inspected in one pass via multiple adjacent focal zones. Referred to as Multi-Zone Inspection, this approach comes at a higher cost in transducers, instrumentation, and set-up time.

A problem observed when applying a highly focused inspection to billets is the potential for misalignment when focusing to the center of the billet. A small transducer positioning error in either angle or translation can produce a substantial displacement of the focused beam at the billet center, as depicted in Fig.(1). When this occurs, a volume at the center of the rotating billet is never inspected. It was observed that this problem can be mitigated by repeatedly sweeping the focused beam about the billet center as the billet rotates, as indicated in Fig.(1c).
The work reported here examines phased array technology as a possible alternative for implementing the uniform focus inspection. Established phased array practice uses Dynamic Depth Focusing (DDF) to maintain a uniform focus response in depth, by manipulating the receiving aperture focus at the rate of pulse propagation, such that reflected signals are received in focus at all reflector depths. Angular scanning is achieved by applying linear phase adjustments over the width of the transmitting and receiving apertures. This work reports on the design of a transducer and associated operating protocol which implement these established phased array capabilities in a uniform focus billet inspection capable of operating at production speeds.

**TRANSUDER DESIGN**

A phased array transducer is sought capable of sweeping a focus in depth to the center of a 10 inch diameter titanium billet, and sweeping the focus at the center of the billet over a small angular range, as depicted in Fig.(1c). Previous studies in the FAA ETC determined that a 65% bandwidth 5 MHz pulse focused to a 6 dB response diameter of 0.1 inch provides adequate signal-to-noise for detection of a #2 FBH-equivalent (2/64 inch dia. flat bottom hole) defect in the titanium alloys of interest. A 5 MHz segmented annular array design was pursued to meet the specified focusing and beam sweeping requirements, assuming a 3 inch transducer-to-billet water path. A criterion to be met in specifying array element boundaries is the restriction of phase variation over each element to a maximum of 1/6 wavelength, when considering the transit time to each point of focus for which a particular element will be used. An additional criterion to be met in specifying element boundaries is the need to maintain as nearly uniform element area as possible, to minimize electrical impedance variation and the resulting variation in element response sensitivity. Because of the equal area requirement, it is noted that the total number of elements required to meet performance objectives is by-and-large determined by the size of the smallest element dictated by the 1/6 wavelength phase error criterion. Many commercially available phased array instruments accommodate a number of elements (i.e. number of individual pulsers and receivers) greater than the number of available time delays. Common configurations have 128 pulser/receivers multiplexed to 32 or 64 time delays. This capability serves in equalizing element areas by allowing larger elements meeting the 1/6 wavelength criterion to be subdivided by a factor of 2 or 4, with each element subdivision driven by its own pulse/receiver, while being tied to a single time delay.
The sequential steps followed in the design process are 1) specify the range of focus in depth and angle, 2) determine optimum transducer surface geometry for focusing over this range, 3) determine annular ring geometry and annulus segmentation meeting the 1/6 wavelength phase error criterion, 4) further refine the annulus segmentation to equalize element areas. Software was developed to perform these geometric determinations, using the specified range of focus as input. The range of sweep in depth is fixed to the radius of the billet (5 inches). The range of sweep in angle was incrementally increased until the total number of elements in the design reached a designated maximum instrument capacity. Designs were carried out for instruments having 32, 64, and 128 time delays. It was determined that use of a 64 time delay instrument could provide an angular sweep covering 0.26 inches about the billet center while meeting the 1/6 wavelength phase error criterion. This was judged acceptable. The properties of this 64 delay design are summarized below.

The challenge to be met in array design is to find an arrangement of array elements which will focus with uniform response to a specified range of positions using a minimum number of array elements. The number of elements required to achieve the desired performance depends on how closely the geometry of the array surface approximates the Fermat surfaces (surface of equal travel time) associated with the desired points of focus. It is noted that focusing to any single focal point can be performed using a single element, that being in the shape of the Fermat surface associated with the targeted point of focus. The number of elements required to focus to multiple focal points is minimized by using a transducer surface which, in some sense, represents the average of the Fermat surfaces of each of the specified focal points. It is shown in [2] that the optimum transducer surface has, at each point on the surface, a normal vector which is the mean of the Fermat surface normal vectors associated with the extreme points of focus within the specified range of operation. By “extreme points of focus” it is meant that pair of focal points having the largest angle between Fermat surface normal vectors at a given transducer surface location. As an example, Fig.(2) depicts the extreme points of focus for the billet inspection. Point A denotes the nearest point of focus. It is noted that the aperture size required to generate a 0.1 inch dia. response diameter depends on the depth of focus, with aperture diameter increasing in proportion to focal depth. Therefore outer diameters of the transducer are not used when focusing close to the billet surface, or conversely, the near extreme point “A” moves progressively deeper with increasing radial position on the transducer face. The center of the transducer is used in focusing to all depths, whereas the outer edge of the transducer is used only in focusing to the billet center. The extreme points “C” and “D” denote the limits of the beam sweep at the center of the billet. The extreme points of focus
used in specifying the transducer normal vector at some given position on the transducer surface will therefore be the depth “A” associated with that position on the probe face, and either point “C’ or “D”, depending on whether the probe face position is to the left or right of the probe center. The normal vector of the optimum transducer bisects these two extreme normal vectors, as depicted in Fig.(2b). Since the surface is specified by its normal vector, the geometry of the surface is computed by starting at the transducer center (located 3 inches above the billet) and integrating outward in all directions. A surface generated in this fashion is referred to in [2] as a Mean Fermat Surface.

Angular sweeping of the beam is to occur in the plane perpendicular to the billet axis. It follows that the 1/6 wavelength phase error criterion will restrict element size most severely in this direction. Consequently, the phase error restriction encountered in this direction is used to determine annular ring width, using the extreme points of focus shown in Fig.(2). The annular ring width is specified in the plane passing through the center of the transducer perpendicular to the billet axis. Following this specification, the full geometry of each annular ring boundary is drawn on the transducer surface as a line of constant phase for focal points located on the transducer central axis. This approach results in each annular ring being associated with a minimum focal depth, thereby allowing a simplified aperture control.

Angular segmentation of the array is performed by noting phase variation as the ring is traversed circumferentially when focusing to points “C” and “D”. Segment length is limited to assure no more than 1/6 wavelength phase variation over the element when focusing to either of these points. Further segmentation is then performed to equalize element areas. Element areas are always decreased in this process, hence compliance with the initially established 1/6 wavelength phase error criterion is assured.

The geometry and element layout of the array transducer for 10 inch billet is shown in Fig.(3). The transducer has approximately elliptical dimensions of 4.08 x 2.67 inch. The array contains 98 elements, and requires 63 delay channels to execute the designed angular sweep. The design purposefully restricted the number of required delays to 63 so that the 64th delay can be used to control a separately mounted transducer for near-surface inspection, shown in Fig.(4a). A microdot connector was integrated into the housing of the array for connecting the separately mounted near-surface transducer, and a mounting collar to hold the transducer adjacent to the array transducer was fabricated. By using a shorter water path (or delaying the array transducer activation), the near-surface transducer signal can be positioned in time prior to the initial array response, thereby allowing the near-surface inspection and volumetric array inspection to be collected in the same waveform.

Note in Fig.(3) that all element dimensions in the horizontal direction are approximately equal, and that longer element dimensions only occur in the vertical direction. This observation arises from the fact that angular sweep is performed in the horizontal direction. Element pairs denoted “a” and “b” are physically wired together, thereby appearing as a single element to the system electronics, with a combined area approximating the targeted element size. This combining of symmetrically positioned elements was key to meeting the design goals. Using this approach, variation in element area was maintained to within 27% of the median value. Profiles of the transducer surface geometry are shown in Fig.(4b) at 0 degree (horizontal), 45 degree, and 90 degree orientations (note the unequal scales of the plot axes).
Use of Dynamic Depth Focusing (DDF) is crucial to implementing the phased array inspection at production rates. DDF manipulates the receiver focus in dedicated electronic hardware at the rate of pulse propagation, so that reflected signals are received in focus at all reflector depths. This allows a single pulse firing to present a focused response at all depths. Because DDF is only applied to the receiver, the focused response is not perfectly equivalent to a conventional matched focused transmitter and receiver. However, through manipulation of the transmit beam geometry and the DDF receiver aperture diameter as described in [3] and [4], it is possible to obtain a uniform focused response well within the 0.1 inch diameter target. Beam angulation is obtained by applying time delays across the active aperture in the direction of angulation, where the delays vary linearly with distance. Importantly, the dynamic delay profile executed by the DDF electronics is the same for all beam angles: only the initial delay profile changes with each beam angle.
Attempting to perform a complete angular scan of the billet center at each rotational data acquisition point presents the likelihood of significantly slowing down the inspection. It is noted that, given proper transducer alignment, the center of the billet is redundantly inspected as the billet rotates. Therefore, rather than performing a complete angular scan at each acquisition point, it is possible to fully cover the billet volume using the angular sweep by incrementing the sweep angle with each successive acquisition point. For example, say 1000 pixels are being collected per billet rotation, and 10 angular increments are desired in sweeping the beam over the billet center. By incrementing the beam angle with each successive acquisition point, the sweep of the billet center will be completed every 10 pixels, and the billet center will be swept 100 times per rotation. It was established that full volumetric coverage is assured using this approach, with negligible sensitivity to transducer misalignment.

**PERFORMANCE VERIFICATION**

The array design depicted in Fig.(3) was fabricated by Imasonic, and tests were conducted to verify its performance. Beam propagation models were used to predict the focusing characteristics of the array. Model predictions of the beam sweeping performance at the billet center are presented in Fig.(5). Single frequency 5 MHz computations of wave field amplitude were obtained, and the square of the field amplitude is plotted as a function of position along the billet radius perpendicular to the direction of pulse propagation. The plots serve to predict inspection signal amplitude in response to an ideal point reflector, as a function of reflector radial position. Beam profiles are compared for 9 different sweep angles, with the largest angle displacing the beam nearly 0.5 inch from center. It is seen that a 0.1 inch 6 dB response width is maintained at all angles. The phased array was designed to meet the 1/6 wavelength phase error criterion when sweeping the beam up to 0.13 inch from center. Fig.(5) demonstrates the consequence of exceeding this limit. At a sweep distance of 0.13 inches from center, the response amplitude is reduced 0.7 dB, due primarily to the accumulation of phase error with increasing sweep distance. Increasing sweep distance, and hence phase error accumulation, beyond this limit introduces a graceful degradation of performance. It is seen that the response is down 6 dB at 0.4 inches, which could be acceptable in many applications.

Experiments were carried out to verify the performance predicted in Fig.(5). Profile measurements of the beam generated by the array were measured on the face of a chord block cut through the center of a 10 inch titanium billet. The transducer was positioned and programmed to sweep a beam focus over the center of the billet, in a fashion intended
FIGURE 6. Beam profiles at 9 sweep angles about billet center: (a) C-scan maps (maximum amplitudes are normalized), (b) vertical line profiles through center of (a), (c) model predictions of beam profiles.

FIGURE 7. Measured FBH response at billet center: C-scan and line profiles through FBH response.

to duplicate the theoretical predictions of Fig.(5). The focal point of a highly focused probe was scanned over a 1.41 by 0.47 inch region on the face of the chord block centered about the billet center, and responses were recorded for each of 9 different beam sweep angles. C-scan maps of the recorded signals are shown in Fig.(6a). A plot comparable to that of Fig.(5) was constructed by superimposing line profiles taken through the center of the 9 images of Fig.(6a). The line profiles are compared to corresponding model predictions in Figs.(6b,c). It is seen that the array is performing well in accordance with model predictions. Measurements of flat bottom hole responses were obtained using a second chord block with 1/64 inch dia. flat bottom holes located at a 5 inch depth on the billet center. Measurements of beam width in the axial direction were made by mechanically scanning the array transducer in the direction of the billet axis. It is noted that, because the FBH is positioned at the center of rotation, rotating the chord block does not provide a measurement of beam width in the circumferential direction. To measure the
beam width in this direction, the electronic beam sweeping capability of the transducer was utilized. At each axial position, the focused beam was swept electronically over 0.25 inches about the billet center. It is seen in Fig.(7) that the 6 dB FBH response width is comfortably within the required 0.1 inch diameter.

ONGOING WORK AND FUTURE IMPLEMENTATION

Upon verification of the array transducer performance, efforts pursued the implementation of the array in a production-ready inspection. Software was written for control of the array beam formation and data acquisition using an Olympus Focus LT instrument with 64 time delays interfaced to 128 element channels. Specialized trigger control schemes were developed to increment beam sweep angle with each rotational pixel acquisition, and DDF control schemes were written to closely approximate the ideal uniform response with depth, so as to meet the established sensitivity requirements. Data display software was developed to merge the angular sweep data into a single C-scan of the billet volume, providing an easy to interpret image of the inspection result. As mentioned above, the array was designed to accommodate a separate near surface inspection transducer attached to the casing of the phased array. However, it was determined that sufficient near surface resolution is obtainable by forming a small aperture beam using only a few of the array central elements. Importantly, it was also observed that data collection occurs sufficiently fast to allow the collection of two signals at each rotational pixel when running at production speeds: the first providing near surface inspection, the second collecting the angulated DDF inspection of the billet volume. Either method of assuring adequate near-surface resolution can be called upon in the future. A performance demonstration of the prototype phased array billet inspection was held in April 2010 at West Penn Testing in New Kensington, PA, which was attended by several representatives of engine manufacturers and material suppliers. Production ready inspections of billets were performed, and the features of the control and analysis software were demonstrated. The option of future implementation was unanimously supported.

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REFERENCES