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Ultrasonic Phased Array Implementation of the Inside Diameter Creeping Wave Sizing Method

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ABSTRACT

This paper describes a technique for implementing the ultrasonic inside diameter (ID) creeping wave technique for detection and sizing ID connected defects using a phased array ultrasonic system. The technique uses multiple focal laws to produce the examination modes. The first focal law is designed to create a shear wave nominally at the critical angle for mode conversion to a longitudinal wave at the ID of a part, thus creating a creeping wave. This focal law is focused at the ID to improve sensitivity. The rest of the laws are designed to create tandem sound paths that progress up a vertical surface directly above the focal point of the creeping wave generation point. When a defect on the inner surface is detected with the creeping wave, the height of the defect can be measured from the response of a set of tandem laws without readjusting the position of the probe. Results from standard 1-inch long notches of varying depths are presented.

INTRODUCTION

An accepted and practiced technique for the ultrasonic detection and sizing of cracks is the inside diameter creeping wave (IDCR) approach.[1] The technique is typically implemented in steels using specialized transducers that produce a nominal 70° refracted longitudinal (L) wave along with an associated 30° direct shear (S) wave and a 31.5° indirect shear wave produced by an outside diameter (OD) creeping wave. The indirect 31.5° S wave mode converts at the backwall (ID surface) of the test piece to produce an L wave that creeps along the ID surface. The highly sensitive IDCR wave will reflect from shallow ID surface cracks to produce a flaw detection signal. If a crack is of significant depth, it will intersect the sound path of the direct 30° S mode converted into a 70° L at the ID to produce a back reflection that can be received by the transducer for a certain range of material thickness. The primary 70° L wave of the transducer will produce reflections from the upper tip of very deep cracks on the order of 40–50% or greater throughwall thickness. Collectively, the three signals can be evaluated to provide a qualitative estimate of ID flaw height from the ID surface.

An enhancement to the standard manual ultrasonic approach is implemented using the flexibility and visualization capability of a phased array system. A linear array transducer is controlled via appropriate focal laws to optimize both the production of the interrogating ultrasonic waves and their positioning on a defect of interest. The first focal law is that of a shear wave at a critical angle for the longitudinal ID creeping wave mode conversion. The focal law is "focused" at the ID to provide increased sensitivity. Another set of focal laws create a series of tandem (pitch-catch) paths that produce a focused interrogation beam in the vertical plane above the ID creeping wave detection point. An illustration of the technique, shown in Fig. 1, entails peaking the signal from the ID creeping wave on the detected flaw, then observing the response from the set of tandem focal laws to achieve a more precise determination of depth of an ID crack. Calculated transit time for each path is used to set gates and delays for easy evaluation of displayed data.

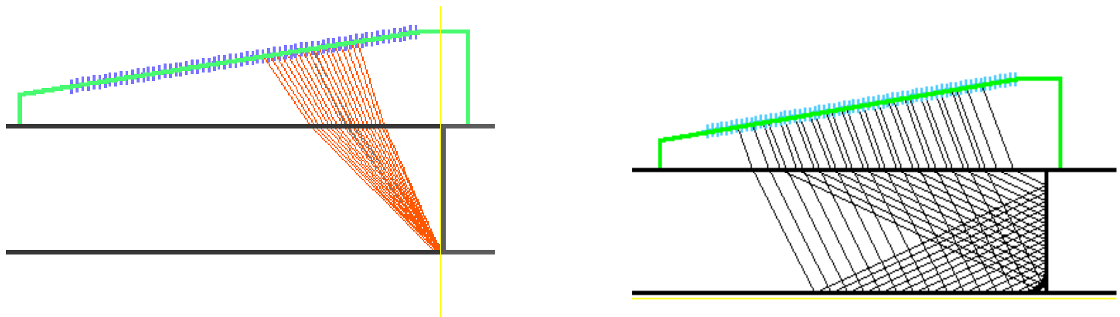

Figure 1. With the phased array probe in the same position, different focal laws can be used to create the flaw detection creeping wave on the left and a set of 30S-70L-70L tandem paths on the right that scan vertically above the focal point of the creeping wave.

For the results in this paper, the tandem beam paths were formed entirely of shear waves without mode conversion to L waves as illustrated in Fig. 1. Using the shear tandem laws reduces the required range of apertures on the linear phased array transducer. The shear waves also have the advantage of no loss of energy due to multiple modes at the reflection interfaces. Data from a study using this technique on a standard notch specimen are presented in the results section.

FOCAL SETUP

The focal laws for the technique described are set up utilizing focal law calculator software to assist in positioning the vertical focal plane in a position where the sound paths for the tandem set of laws can be fit on the available transducer. The vertical target plane is arbitrarily defined as the origin in the horizontal direction. The outer surface of the part is defined as the origin in the vertical direction. The geometry of the wedge and transducer used is incorporated into the focal law calculator. The angle of incidence for the sound beam in the test piece and the part thickness are a variable that is adjustable by the user. The position of the wedge/transducer with respect to the origin is also adjustable.

The tandem set of laws is most constrained so it is developed first. A screen capture of the tandem focal law calculator is shown in Fig. 2. The target locations for the tandem laws are chosen at 0.5-mm increments from top to bottom of the vertical plane. A ray is traced from each target location back at the chosen angle of incidence through the refraction to where it intersects with the transducer. The return ray is traced from the target, reflecting off the bottom surface, through the refraction interface and to the transducer. For fitting the laws on the transducer, the extremes of the aperture range are created by the focal laws directed at the outer (top) surface. By adjusting the position of the probe, the aperture is made to “fit” on the transducer. The gray lines in Fig. 2 show the path of the individual focal laws. The blue (transmit) and red (receive) lines show the sound path to the target of each transducer element used in one focal law. If the extreme sound path fits the rest will fit. For each aperture, the nearest half element (i.e., we allow the center of the aperture to be between two elements when the intersection is closer to the space between elements than the center of either adjacent element) to the intersecting ray is determined. If the nearest half element is the center of an element, a specified number of elements on each side of the center element are included in the aperture. If the nearest half element is between two elements, the same number of elements is used on each side making the aperture one less. As with any focal law calculation, the time of flight from the element to the

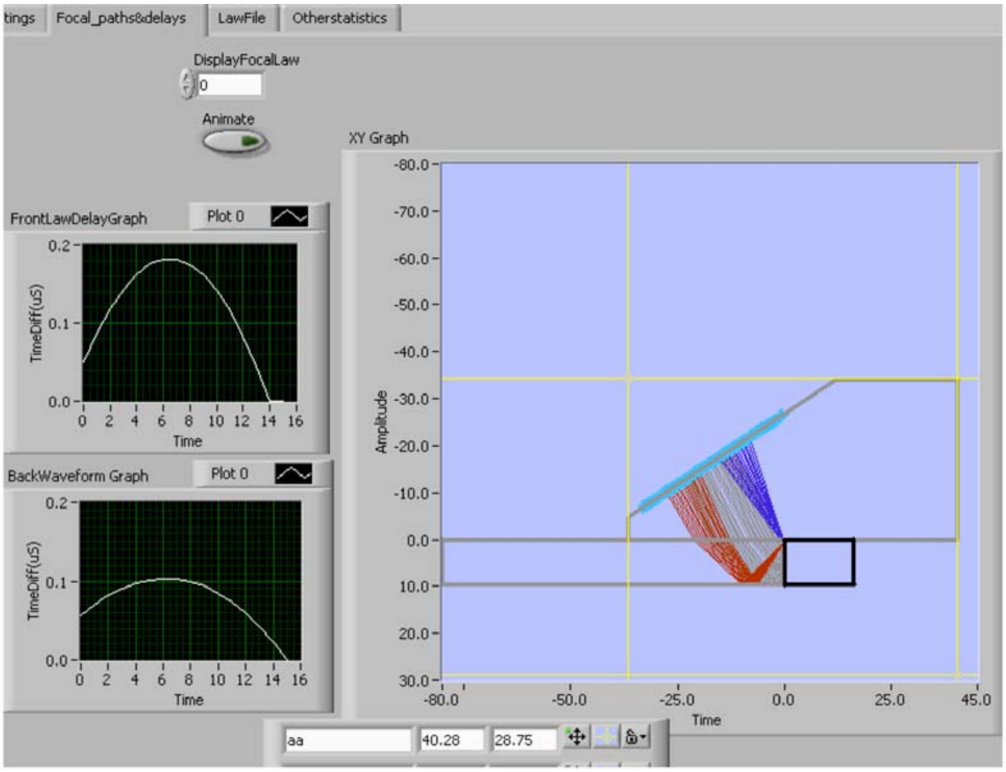

Figure 2. A screen capture of the focal law calculator for generating the tandem set of focal laws. The wedge is shown on top of the material being examined. The gray lines show the path for each law. The blue and red lines show one focal law. The blue is the transmit aperture to the focal spot on the vertical plane. The red shows the receive aperture focused on the same spot but on a path reflected off the bottom surface.

target along the solution path connecting them are computed based on sound speed of the material and wedge. The longest path on each half becomes the zero delay point for the focal law. The expected time of flight for the sound path is taken as the longest path from the transmit path plus the longest path on the receive path. This allows an artificial delay to be inserted into the phased array hardware or display software to make any reflected signal from the focal laws show up at the same time of flight. The same timing gate can be applied to all of the signals.

The focal law to generate the creeping wave is determined next with a shear wave pulse echo mode. Fig. 3 is a screen capture of the focal law for the creeping wave generation. The position of the wedge is the same as for the tandem focal laws. The angle for the shear wave that is at the critical angle of the mode conversion to a longitudinal wave is calculated with Snell's law and the ratio of the longitudinal and shear wave velocities. A ray is traced from the target at the bottom of the vertical plane at the critical angle to the transducer to determine the center half element of the aperture. The remaining element delays are computed to focus at the bottom of the vertical surface.

Some phased array equipment is known to limit the number of focal law groupings to only one. The focal laws used in this paper combine the creeping wave and the set of tandem laws into one channel. By putting the creeping wave as either the first or last law in the group, it can easily be found and displayed as an A-scan or ignored in a volumetric image view. To utilize

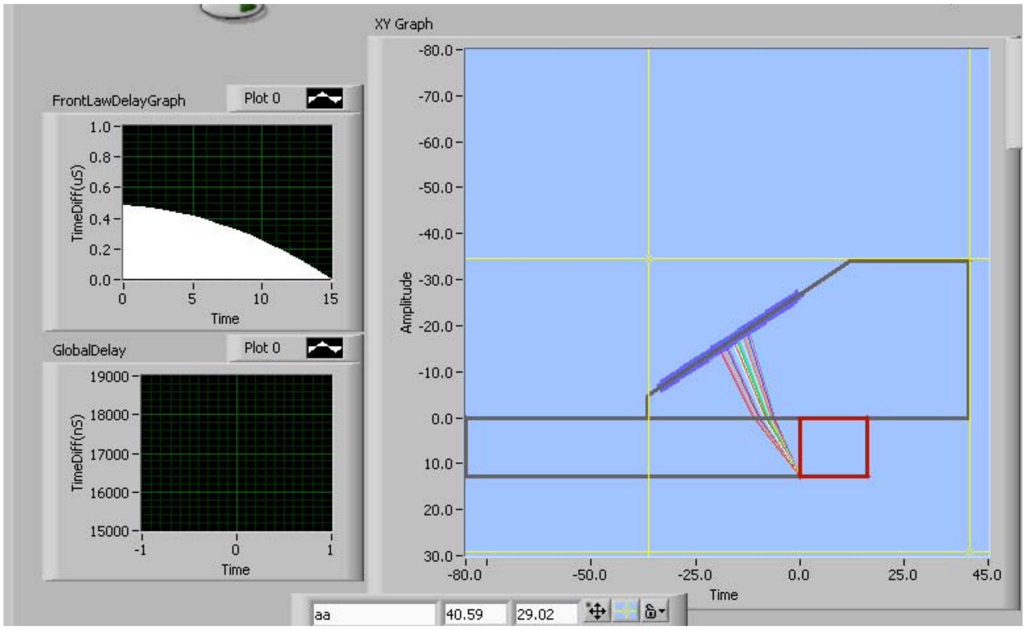

Figure 3. A screen capture of the focal law calculator for generating the creeping wave. The wedge remains at the same location with respect to the vertical surface. One focal law is calculated to form a shear wave focused at the bottom surface on the path of the critical angle for the longitudinal mode conversion.

existing analysis software, the laws are set up to provide the required display. The tandem laws are called 0° sound paths with the sound entry point as the depth of the target position. As mentioned before, an artificial delay is inserted to allow the expected arrival time of a reflection off the entire vertical surface to be displayed at a consistent time. If the creeping wave is included in the same channel of focal laws, it is also designated as a 0° focal law with sound entry position as outside the range of entry positions for the tandem to remove confusion with each other.

TECHNIQUE

In an examination where a part of weld is being scanned for defects originating from the ID or bottom side of the part, a screen is set up on the phased array system to view the creeping wave as an A-scan. The timing of the creeping wave is known either by the approximation used in the calculation of the focal law or from a calibration block. When an indication is generated by the creeping wave, the position of the transducer can be varied to maximize the amplitude of the response. When that point is established, the display of the phased array system is put into a mode to present a volume corrected view of the tandem focal laws. The display shows the vertical depth of the data in a volume corrected view. The depth of the flaw is simply the elevation of the last focal law to record a response from the flaw minus the thickness of the material. The result section shows examples of how this information is displayed and can be analyzed. Further work to determine the most dependable measure for determining this point is planned in the near future.

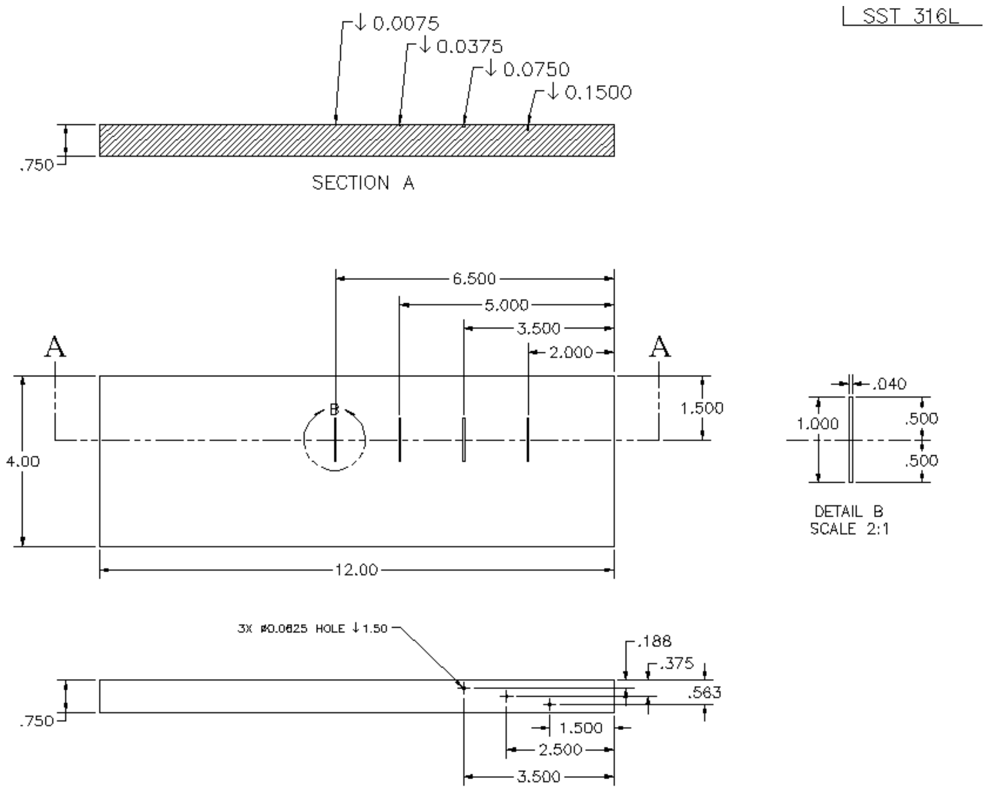

Figure 4. Drawing of notches used. Notches are in 0.75 in. thick plate. EDM notches from smallest to largest are: A) 0.0075 in. (0.2mm), B) 0.0375 in. (0.95 mm), C) 0.075 in. (1.9 mm), and D) 0.15 in. (3.8 mm).

RESULTS

To demonstrate the method, a 0.75-in. (19-mm) block of 316L stainless steel with 1-in. (25.4mm) long electrical discharge machining notches of various depths (1%, 5%, 10%, and 20% thickness) was scanned. Fig. 4 shows a drawing of the block scanned. The equipment used to obtain the results was RD-Tech's Tomoscan III phased array instrument, Tomoview 2.2 software, run on a personal computer connected to the instrument via Ethernet, 5L64 transducer (64 element 0.6 mm pitch), and N45S Rexolite wedge. The apertures used were either 15 or 16 elements depending on the half element center position of the sound path. The vertical target positions of the tandem sound paths range from top surface to bottom surface (0.5 mm to 19.0 mm) at 0.5 mm increments. Each notch was scanned, and the creeping wave response maximized. The display was configured to show both the A-scan of the creeping wave and a volume view of the tandem laws. Cursors were set at the expected time of the return on the tandem sound path. As seen in Fig. 5, the tandem laws are shown on the left in a pseudo volume corrected image, and the creeping wave is shown as an A-scan on the right. The pseudo volume image of the tandem indications is constructed by displaying the A-scan data from each law with time in the horizontal axis and depth of the target for each law, determining the location that the data are presented on the vertical axis. Amplitude is shown as a symmetric gradient about 0 (white/blue as low amplitude green/orange/red as higher amplitude). It is important to note that

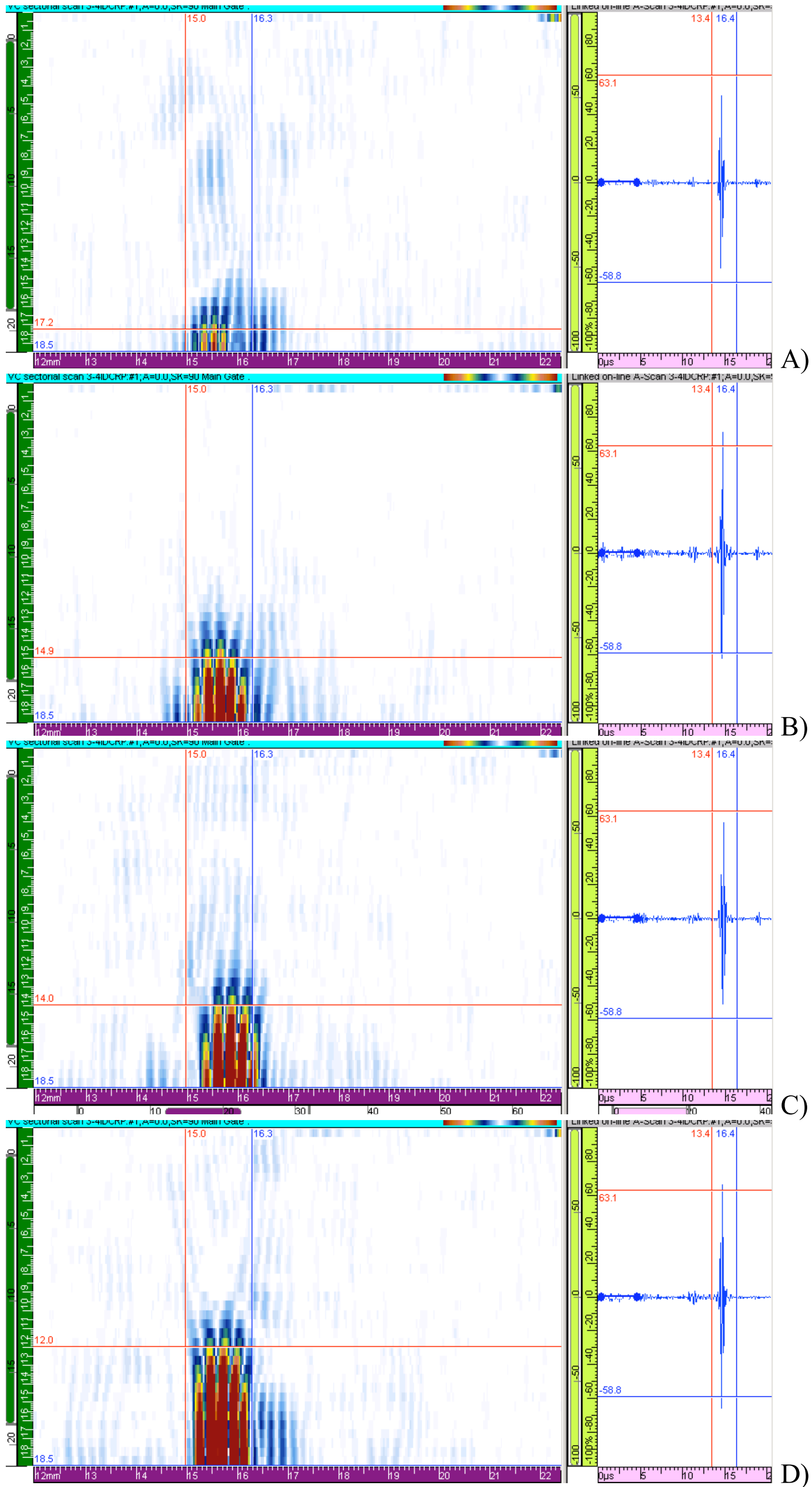

Figure 5. Results for the technique applied to the notched plate. Response to the creeping wave is shown on the right. Tandem response is shown on the left of each. Notches are in 0.75 in. (19.0 mm) thick plate. EDM notches from smallest to largest are: A) 0.0075 in (0.2 mm), B) 0.0375 in. (0.95 mm), C) 0.075 in. (1.9 mm), and D) 0.15 in. (3.8 mm).

the only portion of the signal that is explicitly of interest in the tandem data is that at or near the expected time of flight. Although a range of time is shown in the display, it could be gated with some reasonable tolerance around the expected arrival time. A flaw that is not precisely vertical may still produce an interpretable result although with a time shift.

For a first cut sizing approximation, the horizontal cursor in the tandem view was set at the height where the response attenuated to below 50% response of the peak in the entire wave packets. Note that no formal calibration methodology has been developed, so this is the first attempt at analysis. The "height" of the response varies directly with the height of the notch. Subtracting the height of the cursor placement from the thickness of the plate gives an initial estimate. This results in estimates of A) 1.8 mm, B) 4.1 mm, C) 5.0 mm, and D) 7.0 mm, with the letter designation corresponding to that in Figs. 4 and 5. This produces a near constant error for notches B)-D) of approximately 3 mm larger than the actual height. Notch A) is small and does not comply with that trend. A further refinement in the height approximation can be made by carefully looking at the first radio frequency (RF) pulse nearest the expected time. By looking at the 50% cutoff of that first pulse, target A) is essentially measured as 0 mm. Given the small size, it is a reasonable result to have it detected by the creeping wave but not measured with any significant height by the tandem method. The other targets result in approximate heights of B) 2.0 mm, C) 2.5 mm, and D) 5.0 mm. Analysis in this mode again overestimates the size but with a smaller error between 0.5 mm and 1 mm. A detailed analysis of the source of the error has not been performed. It is possibly due to a combination of spot size and target position increment (i.e., incrementing at 0.5 mm would set a limit without attempting to interpolate). Since moving the center of the aperture by half-element steps produces the 0.5-mm increments, smaller increments to achieve greater resolution with the given transducer are not possible.

The reader should be aware that the wedge used for this experiment is not ideal for inspecting close to a weld. A wedge could be designed to more effectively approach a weld's reinforcement when necessary.

CONCLUSION

This paper presents a method for enhancing the IDCR method for sizing of defects utilizing the flexibility of phased array ultrasonic technology. The steps for producing focal laws to implement the method were summarized. The potential of the method was demonstrated on regular notches of varying depth. The depths of regular notches have been estimated to within a 1-mm positive error bound. Future work will include applying the method to actual defect samples, developing calibration methods, and refining analysis techniques.

ACKNOWLEGMENTS

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