Phased Array Inspection at Elevated Temperatures

Mohammad Marvasti[1], Mike Matheson[2], Michael Wright, Deepak Gurjar, Philippe Cyr, Steven Peters

Eclipse Scientific Inc., 97 Randall Dr., Waterloo, Ontario, Canada

E-mail: [1]mmarvasti@eclipsescientific.com, [2]mmatheson@eclipsescientific.com

Abstract
An ultrasonic phased array system is described for online inspections of welds or condition monitoring of parent material at elevated temperatures of up to 350°C. Wedges are built from plastics resistant to high temperature degradation, and equipped with a cooling jacket around the array. A model of the ultrasonic beam skew pattern due to thermal gradients inside the wedge was developed. The model is used in a separate algorithm to calculate transmission and reception time delays on individual array elements for generation of plane waves in a hot test piece, while compensating for thermal gradients effects inside the wedge. The algorithm results were used to develop a high temperature phased array inspection technique (HTPAUT). Experimental verifications of the developed technique indicate that plane waves can be generated efficiently in a hot test piece to locate flaws in the piece within the same level of accuracy achieved through room temperature inspection of the same piece.

Introduction
Interruption of plant operations can be avoided if NDT inspections are performed in-line at operating temperatures; however, there are operational temperature limits for the phased array transducers and associated plastic wedges. Engineers at Eclipse Scientific have developed a unique solution for high temperature phased array (HTPAUT) inspection based on designing high temperature wedges built from materials resistance to high temperature degradation and equipped with a cooling jacket to protect the array. This novel solution facilitates inspection of pieces at temperatures up to 350°C [1]. This system is currently utilized in numerous industrial sites for detection of potential indications in welds, pressure vessels, etc. However, accurate positioning of the detected indications remains challenging [2]. There is an acknowledged limitation in approved, appropriate high temperature inspection techniques for inspection at elevated temperatures. Inside the high temperature wedge, thermal gradients lead to variations in temperature-dependent wave velocity and skewing of the waves; the focal law calculator in a phased array instrument, which is based on the assumption of wave propagation in homogeneous propagation media, would then become inaccurate. Refraction angles of ultrasound into the test-piece are altered by the elevated temperature within the wedge and test material and skewed ultrasound propagation paths results.

The effects of thermal gradients and beam skew inside the high temperature wedges on indication positioning inside the hot piece has been studied by Eclipse Scientific. This led to development of a unique HTPAUT inspection technique to accurately position the detected indications inside hot pieces. The newly developed technique is based on 1) to calculate focal laws for generation of plane waves in a hot test piece, while compensating for thermal gradients effects inside the wedge and 2) to import the newly calculated focal laws in to the phased array instrument to be used for beam generation.

Phased Array Beam Formation
To generate a planar wave which propagates at a certain angle in a homogenous and isotropic medium, the piezoelectric elements should be fired with specific relative time delays known as focal laws. The delay magnitude on each individual element depends on factors such as speed of sound in the medium, spacing between the array elements and desired propagation angle of the beam with respect to the array line.

Once a wedge is used to generate a specific refraction angle in a test piece, Snell's law is used first based on the selected refraction angle and the wedge-test piece velocity ratio to indicate the required beam angle inside the wedge (incident angle). Element delays (focal laws) are calculated to generate a plane wave inside the wedge along the incident angle. The plane wave then refracts along desired refraction angle at the wedge-piece interface.

Focal laws are first calculated through the focal law calculator of the phased array instrument and then applied to the transducer elements through separate electric channels. Once the transducer is connected to the instrument, information such as element spacing, element width, frequency, number of elements, etc. is provided to the instrument for focal law calculation. Wedge information such as velocity of sound in the wedge, wedge angle, height of the first element of the transducer on the wedge, distance from the back and front of the wedge to the first element, etc. is also provided to the instrument for focal law calculation and indication positioning.

Indication Positioning

A set of active elements is fired by the phased array instrument to generate a shear plane wave with a specific refraction angle inside the test piece. The instrument records the total travel time of the sound from the elements to a target indication of the refracted sound path and back to the elements. The total time includes sound travel time inside the wedge (from the center of the active aperture to the exit point) plus inside the test piece (from the exit point to a potential indication) along the refracted beam path.

Propagation path of the generated plane wave inside the wedge and inside the piece are both approximated as a straight line perpendicular to the wave front. Straight sound path length inside the wedge (L_w in Fig. 1) is calculated geometrically based on relative wedge and array information imported in to the instrument. Accordingly sound travel time along this path is calculated using velocity of the sound inside the wedge ($t_w = L_w/V_w$). It should be noted that total travel time inside the wedge is 2× t_w (transmission and reflection) which is known as wedge delay.

Subtraction of the wedge delay from the total travel time recorded by the instrument indicates sound travel time along the refracted path inside the piece from the exit point to the potential indication and back to the exit point. Straight sound path length from the exit point to the indication (L_s in Fig. 1) is then calculated using the velocity of sound inside the piece, L_s = (total time – wedge delay) × $V_w/2$. The indication is then located with respect to wedge position based on the beam exit point location, beam refraction angle inside the piece and the L_s magnitude.

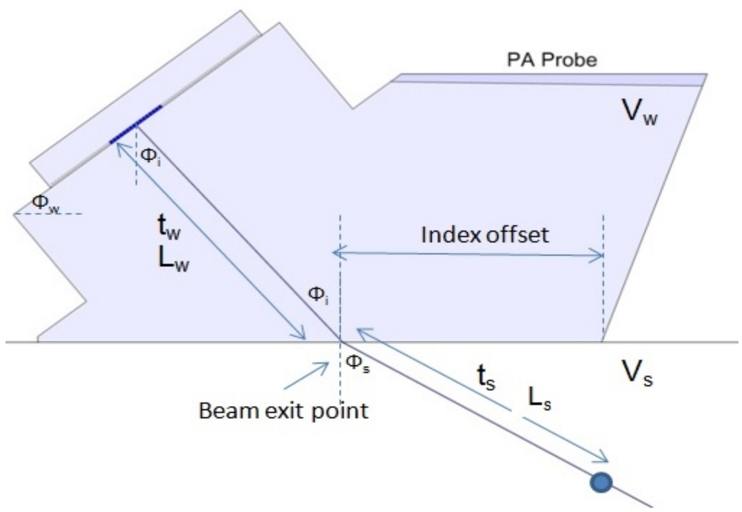

Figure 1: Ultrasound propagation path configuration inside the wedge and a test piece at room temperature.

Law File

After the above described calculations are performed, critical information required for beam formation and indication positioning along each selected refraction angle are stored in phase array instruments. This information includes focal laws, wedge delays, beam exit point (index offset), etc. for each refraction angle. The law file is referenced by the phased array instrument hardware for beam formation and flaw positioning as described above. In some instruments, such as the OmniScan, law files can be exported, modified and re-imported to the instrument. This capability can be used for situations where linear approximation of the wave paths inside the wedge is invalid (inspection at elevated temperatures). This leads to non-optimal beam generation and inaccurate indication positioning. However law files can be modified to adapt the inspection condition.

Inspection at Elevated temperature

At elevated temperatures, inside the wedge, thermal gradients lead to variations in temperature-dependent wave velocity and skewing the waves. Therefore the linear approximation of the sound path inside the wedge is no longer valid. This indicates that information stored in the instrument's law file is no longer accurate and leads to non-optimal beam formation in both the wedge and the test piece, and inaccurate positioning of indications inside the hot piece. This inaccuracy can be resolved if 1) the focal laws are calculated compensating for the temperature dependent sound velocity changes inside the wedge; 2) wedge delay is calculated based on the skewed beam path inside the wedge and 3) velocity of sound inside the piece is modified for elevated piece temperatures.

In order to calculate focal laws for inspection at elevated temperatures, a model of the thermal gradient-induced ultrasonic beam skew pattern inside the wedge is developed. First, the temperature distribution inside the wedge is modeled using finite elements software package and validated experimentally. Next, the dependence of compression wave velocity on temperature in wedge materials is measured experimentally. These were then combined with a numerical ray-tracing technique to model the skewed path of waves propagating across thermal gradients in the heated wedge. The beam skew model is then used in a separate algorithm to calculate transmission and reception time delays on individual array elements for generation of plane waves in a hot test piece, while compensating for thermal gradients effects inside the wedge. Algorithm details are explained in detail in [3, 4].

The algorithm results were used to develop a phased array inspection technique at elevated temperatures: 1) elements delay times recorded in the law file were replaced with the calculated thermal gradient compensated delays, 2) wedge delays were calculated based on travel time along the skewed beam path inside the wedge and updated in the law file and finally 3) sound velocity inside the piece at the inspection temperature is modified in the law file. Once the above modifications were applied to the law file, the law file is imported back into the phased array instrument to be used for beam formation and accurate flaw positioning at elevated temperatures.

Experimental Verification

In order to validate the developed technique an experiment was designed based on scanning a 38-mm thick steel calibration block containing two 2.5-mm diameter side-drilled-holes and two 3-mm notches. Scan plans were built for scanning the calibration block using WA12-HT55S-IH-G and WA12-HT55S-IH-B Eclipse high temperature wedges operating at elevated temperatures of up to 150^{o}C and 350^{o}C respectively.

Fig. 2 illustrates the scan plan built using ESBeamTool6 ray tracing software based on using WA12-HT55S-IH-G Eclipse high temperature wedge and 5L64-A12 Olympus array. The scan plan is built based on using first 16 elements of the array generating a sectorial beamset with minimum and maximum refraction angles of 42^{o} and 65^{o} respectively. The wedge is placed on the test piece with wedge front to the block center distance (index offset) set to 15 mm. This scan plan indicates that at room temperature, SDH 1 (located 11 mm below the block surface), can be detected within the refraction angular range of 47^{o}-48^{o} and sound path range of about 65-67.5 mm based on the thickness of the plate and the location of the SDH from the surface of the plate. Similarly, scan plan based on using WA12-HT55S-IH-B indicates that at room temperature, SDH 1, can be detected within the refraction angular range of 51^{o}-53^{o} once the first 16 elements of the array were used to produce a sectorial beamset with minimum and maximum refraction angles of 50^{o} and 65^{o} respectively. Wedge front to the block center distance is about 15 mm.

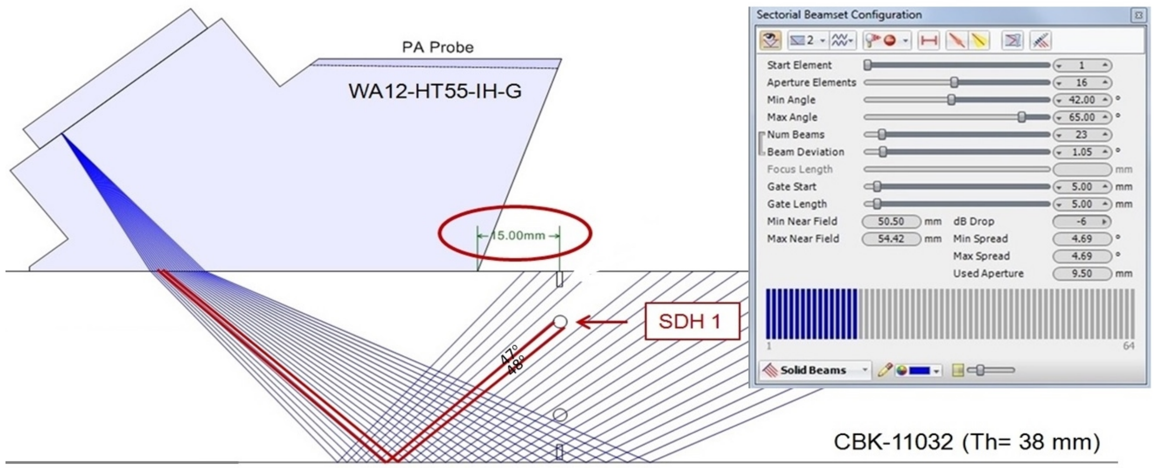

Figure 2: Scan plan built using ESBeamTool6 for inspection of a 38-mm thick block using WA12-HT55S-IH-G High Temperature wedge.

The calibration block was first scanned at room temperature (23°C) with the setting specified by the scan plan. The block was then placed on a hot plate and re-scanned once the block was at 75°C and at 150°C using WA12-HT55S-IH-G wedge and at 200°C and 300°C using WA12-HT55S-IH-B wedge with no change in the settings specified by the scan plan. Scanning was performed twice at each temperature: first, with room temperature law file (focal laws, time delays, wedge delays and piece velocity at 23°C); then with high temperature modified law files (thermal gradient compensated focal laws, wedge delays and steel velocity at elevated temperatures). Scanned data were then analyzed and the angle and the sound path associated with the maximum amplitude response from SDH1 were recorded. The results are summarized in Tables 1 and 2.

Table 1: WA12-HT55S-IH-G Scan Results.

	Maximum Amplitude Response from SDH1		Angle (deg)	Sound Path (mm)
1	Scan Plan	ESBeamTool	47 - 48	67.5 - 65
	23 °C Scan	23 °C Law File	48	65.6
2	75°C Scan	23 °C Law File	47	67.8
		75°C Law File	48	66.6
3	150°C Scan	23 °C Law File	46	70
		150°C Law File	48	66.6

Table 2: WA12-HT55S-IH-B Scan Results.

	Maximum Amplitude Response from SDH1		Angle (deg)	Sound Path (mm)
1	Scan Plan	ESBeamTool	51 - 53	67.5 - 65
	23 °C Scan	23 °C Law File	53	65.6
2	200°C Scan	23 °C Law File	51	71.5
		200°C Law File	53	65.4
3	300°C Scan	23 °C Law File	51	73.5
		300°C Law File	53	66.5

Following points are noted based on the results listed in the above Tables: 1) at 23°C, maximum amplitude response from SDH1 was obtained at angles and sound paths within the range expected, as specified by ESBeamTool6; 2) for elevated temperature scans, the same response was received at different refraction angles when room temperature law files (no compensation for the thermal gradient effects) were used. The indication sound path also deviated from the expected range. This lead to the SDH1 having a positioning error with respect to wedge location; However, 3) once the appropriate high temperature modified law files were used, the maximum amplitude response is obtained at the same refraction angle and sound path range as detected and predicated from room temperature scans. Therefore, it is observed that scanning the block using the high temperature modified law file can retain indication positioning accuracy as of room temperature scans, compensating for thermal gradient effects on sound propagation inside the wedge.

The above experiments were repeated several times at each temperature for results consistency check. Figure 3 illustrates the sound paths which the maximum amplitude response from SDH1was detected vs. block temperatures. The blue and red lines represent the results when room temperature and high temperature modified law files were used by the phased array instrument respectively. The dashed lines represent the expected sound path range (65-67.5 mm). It is seen that as the scanning temperature increases, scan results obtained using room temperature law files deviates further from the expected range. The detection results fall back within the expected range once the high temperature modified law files were used at for inspection at each temperature.

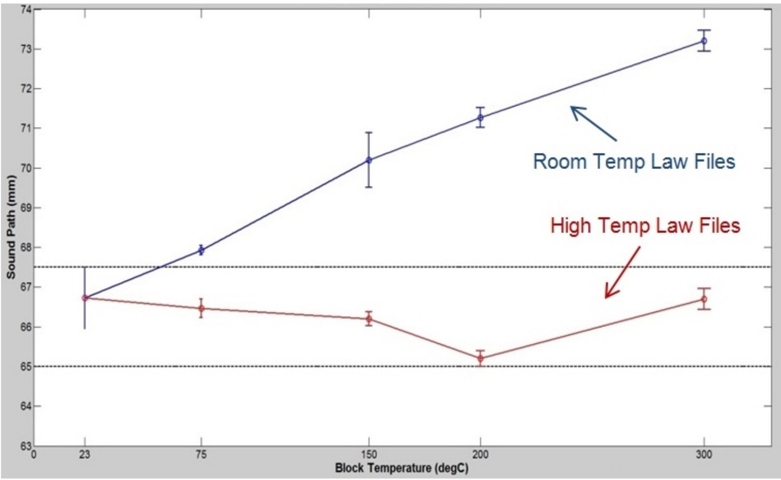

Figure 3: Comparison of the sound path of the maximum amplitude respond of SDH1 using room temperature and high temperature modified law files in the phased array instrument.

Conclusion

Recent research done by Eclipse Scientific has led to the development of a new technique for HTPAUT. The technique is based on utilizing modified law files in phased array instruments with high temperature focal laws and wedge delays calculated using advanced focal law calculation algorithms and beam skew models. Experimental verifications of the developed technique indicate that plane waves can be generated efficiently in a hot test piece to locate flaws in the piece within the same level of accuracy achieved through room temperature inspection of the same piece. Eclipse Scientific will provide the newly proposed technique to the NDT industry through ESBeamTool software. ESBeamTool will provide advanced focal law calculator and law file generator tools to be used along with high temperature wedges to facilitate phased array inspections at elevated temperatures for technicians. These tools lead to accurate inspection with temperature effects compensations on the scan results.

References

[1] http://www.eclipsescientific.com/Products/Scanning/ESTempMaster/index.html
[2] Etherington, L., MacRaild, A., “A Practical Application of Phased Array Inspection at High Temperature”, ASNT Ultrasonics for Nondestructive Testing, July 2015.
[3] Marvasti, M., Bond, J., Matheson, M., and Sinclair, A., “Phased Array Inspection at Elevated Temperatures: effects of Ultrasonic Beam Skew”, *Insight*, Vol. 56, No. 5, pp. 256-263, May 2014.
[4] Marvasti, M., Sinclair, A., “Phased Array Inspection at Elevated Temperatures”, *Ultrasonics Symposium (IUS) IEEE International*, pp. 854-857, 2014.