The effect of ultrasound wave path estimation to defect characterization capability in half-skip total focusing method

Xiangyu Lei[1], Håkan Wirdelius[2] and Johan Carlson[3]
1 Doctoral student at Chalmers University of Technology, Sweden, xlei@chalmers.se
2 Professor at University West, Sweden, hakan.wirdelius@hv.se
3 Professor at Luleå University of Technology, Sweden, johan.carlson@ltu.se

Abstract

The total focusing method (TFM) is a post-processing imaging technique applied on full matrix capture (FMC) ultrasonic inspection (UT) dataset. In TFM the ultrasonic wave energy is synthetically focused on every pixel in the image region of interest (ROI). In terms of half-skip TFM (HSTFM), wave mode conversion happens when the wave rebounds at interface, such as specimen backwall. This paper aims to propose and evaluate a method that involves Snell's law to address accurate estimation of distance-of-flight (DOF) of wave propagation when wave mode conversion appears in HSTFM. This HSTFM algorithm is applied to both experimental and simulated FMC dataset that inspects a surface-breaking notch for notch image reconstruction. Comparisons between images with and without considering Snell's law in wave mode conversion show visible difference that could lead to misinterpretations in characterizing the defect. The sensitivity of TFM to varying defect features such as defect tilt angle is also studied using simulated FMC datasets.

KEYWORDS: Ultrasonic array; Total focusing method (TFM); Defect characterization

1. Introduction

With the increasing application of ultrasonic array techniques in nondestructive testing (NDT), full matrix capture (FMC) data acquisition strategy is developed based on the individual transmitting and receiving ability of array probe elements. FMC dataset contains the complete set of time-domain signal from all possible transmitter-receiver pairs of an array probe [1]. To make the most of the information contained in FMC dataset, an imaging algorithm called total focusing method (TFM) can be applied, which synthetically focuses the ultrasonic wave energy on each image pixel in the image region of interest (ROI) [1]. In general, TFM can be grouped by three modes depending on the presumed wave path configurations [2], i.e., direct path, half-skip and full-skip path. They indicate no wave rebounds, either the transmitting or receiving wave rebounds once [3] and both paths rebound on the specimen backwall, respectively.

 https://doi.org/10.58286/28202

It has been shown beneficial in detecting and sizing surface-breaking notches or cracks [4][5] using half-skip TFM (HSTFM) since it counts the reflected wave signals from defect surface. However, care must be taken when wave mode (either longitudinal or transverse wave) converts at intersection, so that an accurate estimation of distance-of-flight (DOF) of wave in TFM delay-and-sum process can be achieved. This contribution hereby investigates the effects of Snell's law based wave mode conversion in HSTFM in terms of defect characterization capability.

2. Description of Snell's law based wave mode conversion in HSTFM

Considering the general test specimen in Figure 1 with height of h. Ultrasonic wave travels from transmitter (tr) at coordinate $(x_{tr}, 0)$ to receiver (re) at coordinate $(x_{re}, 0)$ through wave path L_1-L_2-L_3. The coordinate of the imaging pixel P is given by (x_p, z_p). Based on the symmetry of path L_2 to backwall, a mirror pixel P_m is located at coordinate $(x_p, 2h - z_p)$. When there is no wave mode converts at backwall (the incident wave angle θ_i equals the reflected wave angle θ_r), wave can be seen as directly propagated from the transmitter to the mirror pixel P_m (i.e., along L_1-L_2), then from pixel P to receiver (i.e., along L_3). If wave mode converts at backwall, θ_i will be different from θ_r and follows Snell's law [6]. It is thus important to find the bounce point B with coordinate (x_b, h).

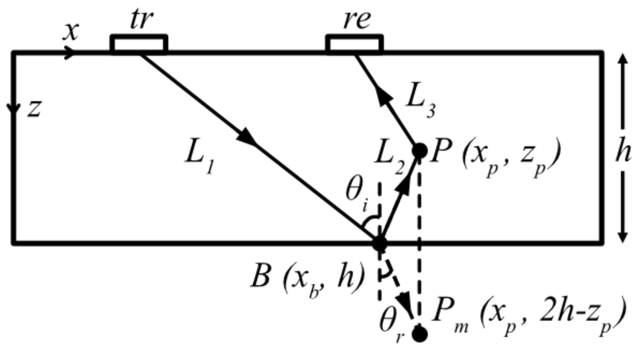


Figure 1. Schematic illustration of HSTFM wave path with Snell's law based wave mode conversion

For incident wave angle θ_i and reflected angle θ_r, geometrical relation gives:

$$sin\,\theta_i = \frac{x_b - x_{tr}}{|L_1|} = \frac{x_b - x_{tr}}{\sqrt{(x_b - x_{tr})^2 + h^2}} \tag{1}$$

$$sin\,\theta_r = \frac{x_p - x_b}{|L_2|} = \frac{x_p - x_b}{\sqrt{(x_p - x_b)^2 + (h - z_p)^2}} \tag{2}$$

Given the incoming and reflected wave speed of c_i and c_r, Snell's law requires that:

$$\frac{sin\,\theta_i}{c_i} = \frac{sin\,\theta_r}{c_r} \tag{3}$$

Combine Equations (1)-(3) gives a function of unknown coordinate x_b as Equation (4), so that x_b can be found by letting $f(x_b) = 0$.

$$f(x_b) = \frac{x_b - x_{tr}}{c_i\sqrt{(x_b - x_{tr})^2 + h^2}} - \frac{x_p - x_b}{c_r\sqrt{\left(x_p - x_b\right)^2 + \left(h - z_p\right)^2}} \tag{4}$$

The length of L_1 and L_2 can then be calculated by:

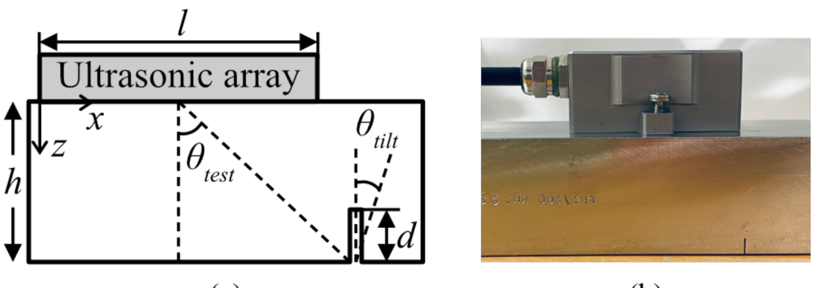
$$L_1 = \frac{x_b - x_{tr}}{sin\ (\theta_i)} = \frac{x_b - x_{tr}}{sin\ (tan^{-1}(\frac{x_b - x_{tr}}{h}))} \tag{5}$$

$$L_2 = \frac{x_p - x_b}{sin\ (\theta_r)} = \frac{x_p - x_b}{sin\ (tan^{-1}(\frac{x_p - x_b}{h - z_p}))} \tag{6}$$

3. Inspection scenario for FMC dataset

The HSTFM with Snell's law based wave mode conversion is in this contribution applied on FMC dataset inspecting a surface-breaking electric discharge machined (EDM) notch, intended to compare the reconstructed images with the one without considering Snell's law. This is implemented by only assigning different wave speeds to corresponding wave paths (L_1 and L_2).

The inspection scenario is shown in Figure 2, where the ultrasonic array probe is placed on top surface of a test specimen (made of stainless steel with longitudinal and transverse wave speed of 5573 m/s and 3150 m/s, respectively) with height h = 35 mm and contains an upright ($\theta_{tilt} = 0^o$) surface-breaking EDM notch of size d = 5 mm. Coordinate system origin is set at bottom-left end of probe. The used array probe is a longitudinal wave linear phased array (PA) probe labelled LM-5MHz (center frequency of 5 MHz and bandwidth of 74%, total length of l = 38.3 mm) produced by Zetec. The angle between the probe center and notch root is $\theta_{test} \approx 36^o$ so that the horizontal distance between them is $h * tan(\theta_{test}) = 25.4$ mm, which is larger than half of probe total length (19.2 mm). In this way, the notch is not covered by the probe projection area, so that the notch indication in TFM images will not be covered by the "smearing" of backwall reflections [4].



(a) (b)

Figure 2. (a) Schematic illustration of (b) experimental inspection scenario

The FMC dataset is collected through experiments as in Figure 2(b) and through simulations by simSUNDT software [7][8]. The software can simulate the entire testing procedure of UT and present results in terms of various data presentations. Simulated FMC dataset is in this contribution treated as a complement to experiments and for further parametric investigations.

4. Results

HSTFM images are reconstructed in all possible wave mode sequences following L_1-L_2-L_3 in Figure 1. Figure 3 shows the wave mode sequence of LTT that gives clear indications of the notch profile using experimental (Figure 3 (a) and (b)) and simulated (Figure 3 (c) and (d)) FMC dataset of the considered inspection scenario. Figure 3(a) and (b) compare the reconstructed images with and without considering Snell's law based wave mode conversion, same as in Figure 3(c) and (d). It is seen from Figure 3(a) and (c) that the upright notch inspected in Figure 2(b) can be correctly indicated with no tilt angle (0-degree as upright) when involving Snell's law based wave mode conversion in HSTFM image reconstruction. However, if it is not involved in the algorithm, the notch indications shown in Figure 3(b) and (d) could possibly lead to misinterpretations with some visible tilt angles of approximately 15-degrees in anticlockwise direction. Besides, the notch root at depth 35 mm is also indistinguishable in Figure 3(d).

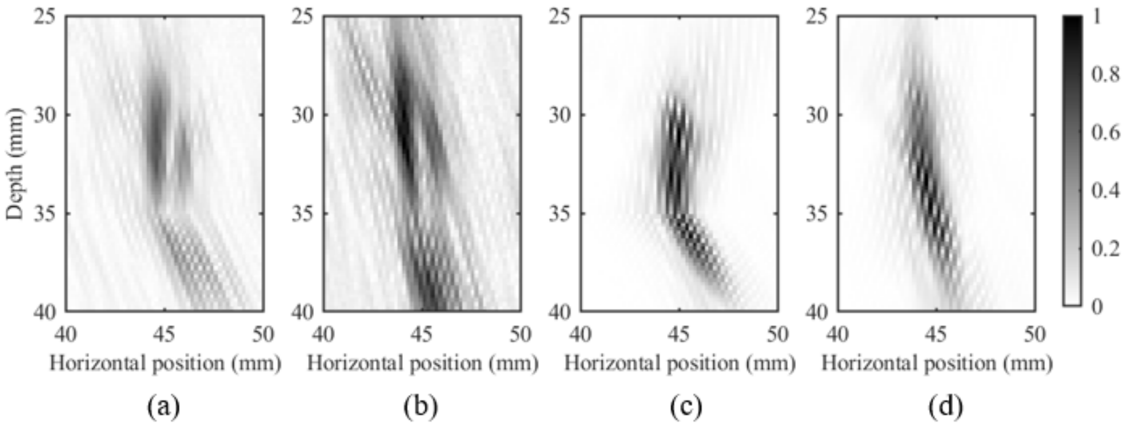


Figure 3. Reconstructed HSTFM images in LTT wave mode sequence based on experimental FMC dataset (a) with Snell's law based wave mode conversion and (b) without Snell's law based wave mode conversion. They are complemented with images of the same wave mode sequence using simulated FMC dataset (c) with Snell's law based wave mode conversion and (d) without Snell's law based wave mode conversion

Based on above observations, it is of interest to evaluate how HSTFM performs on notches that are not upright to specimen backwall ($\theta_{tilt} \neq 0$ in Figure 2(a)). For this purpose, FMC dataset of inspection scenario in Figure 2(a) is simulated in parametric studies using simSUNDT simulations, where the notch tilt angle (θ_{tilt}) is the only variable and is set to be 15-, 20- and 45-degrees in clockwise direction. Notch profile is in these cases clearly indicated in wave mode sequence of LLT shown in Figure 4, where the solid lines illustrate the notch orientation and its angle to the vertical dashed line shows the tilt angle. Note that the wave mode sequence used here is not LTT as in Figure 3. This verifies the sensitivity of TFM images to defect features [9], that not all wave mode sequences can reconstruct the defect profile when defect features are changed.

The sensitivity of TFM imaging can also be noticed when comparing the three cases in Figure 4. The entire notch profile can be reconstructed for notch with tilt angle of 15- and 20-degrees, while the reconstruction fails for 45-degrees tilt angle. Corresponding direct path TFM images in LL wave mode sequence is reconstructed in Figure 5 for further illustration of proper choice of the TFM modes, that only the tip and root diffraction can be observed for notch with 15- and 20-degrees tilt angle, while both diffractions and entire notch profile are visible for 45-degree tilt notch.

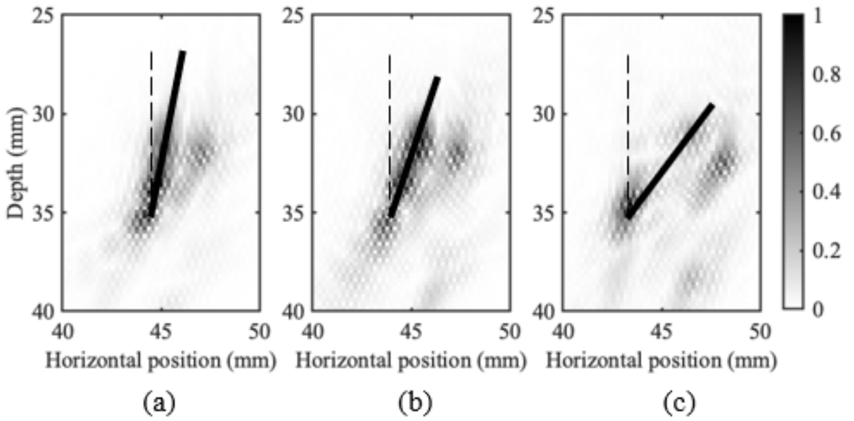


Figure 4. Reconstructed HSTFM images in LLT wave mode sequence based on simulated FMC dataset of inspection scenario in Figure 2(a) with notch tilt angle of (a) 15-degrees, (b) 20-degrees and (c) 45-degrees

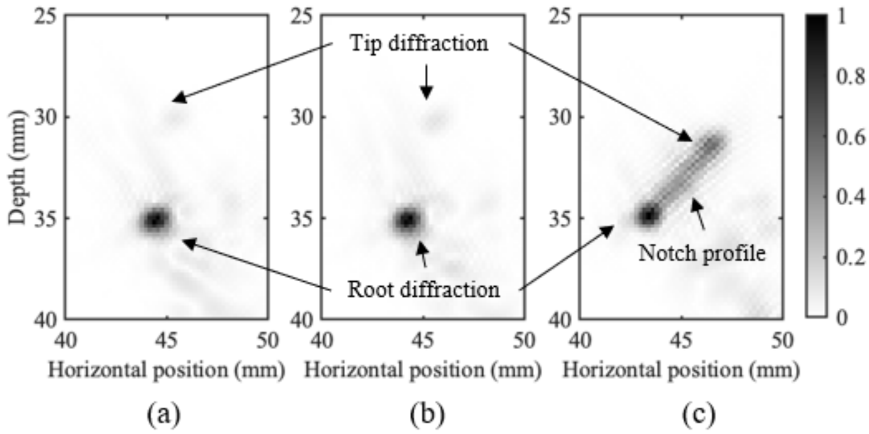


Figure 5. Reconstructed TFM images in direct path (LL wave mode sequence) based on simulated FMC dataset of inspection scenario in Figure 2(a) with notch tilt angle of (a) 15-degrees, (b) 20-degrees and (c) 45-degrees

5. Conclusions

In this paper an idea of Snell's law based wave mode conversion is proposed for an accurate estimation of DOF of wave in HSTFM imaging process. The effect of the proposed method on defect characterization is evaluated by comparing reconstructed HSTFM images with and without involving the method, using experimental and simulated FMC dataset that inspects a surface-breaking notch. It is observed in images of certain wave mode sequence where appropriate that the proposed method could help avoid possible misinterpretations in terms of e.g., defect tilt angle.

In addition, direct path TFM and HSTFM images are reconstructed for some simulated surface-breaking notches with varying tilt angles. This is to illustrate and verify the sensitivity of TFM images to defect features. It can be concluded that different appropriate TFM modes should be combined for a thorough analysis and defect characterization in multi-mode TFM studies.

Acknowledgements

We are grateful to the technical helps from the Swedish Qualification Centre (SQC), where the test specimen with surface-breaking EDM notches is provided in this study.

References

[1] C Holmes, BW Drinkwater, BW and PD Wilcox, "Post-processing of the full matrix of ultrasonic transmit–receive array data for non-destructive evaluation", NDT & e International, 38(8), pp 701-711, 2005.

[2] YU Peng and T Gang, "The Use of Multi-Mode TFM to Measure the Depth of Small Surface-Break Cracks in Welds", In 2017 Far East NDT New Technology & Application Forum (FENDT), pp 106-110, IEEE, 2017.

[3] MV Felice, A Velichko, PD Wilcox and CJ Lane, "Depth measurement of small surface-breaking cracks using the Half-Skip Total Focusing Method", In AIP Conference Proceedings (Vol. 1650, No. 1, pp 994-1000). American Institute of Physics, 2015.

[4] MV Felice, A Velichko and PD Wilcox, "Accurate depth measurement of small surface-breaking cracks using an ultrasonic array post-processing technique", Ndt & E International, 68, pp 105-112, 2014.

[5] J Zhang, T Barber, A Nixon and PD Wilcox, "Investigation into distinguishing between small volumetric and crack-like defects using multi-view total focusing method images", In AIP conference proceedings (Vol. 1806, No. 1, pp 040003). AIP Publishing LLC, 2017.

[6] PJ Shull, "Nondestructive evaluation: theory, techniques, and applications", CRC press, 2002.

[7] H Wirdelius, "The implementation and validation of a phased array probe model into the simSUNDT software", In Proceedings of 11th European Conference on NDT, 2014.

[8] P Bövik and A Boström, "A model of ultrasonic nondestructive testing for internal and subsurface cracks", The Journal of the Acoustical Society of America, 102(5), pp 2723-2733, 1997.

[9] K Sy, P Brédif, E Iakovleva, O Roy and D Lesselier, "Development of methods for the analysis of multi-mode TFM images", In Journal of Physics: Conference Series (Vol. 1017, No. 1, pp 012005). IOP Publishing, 2018.