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Multi-Mode Total Focusing Method (MTFM) to Detect High-Temperature Hydrogen Attack (HTHA) – A Review

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Abstract. High temperature hydrogen attack (HTHA) is a commonly observed harm component in carbon steels exposed to high temperature and pressure in a hydrogen-rich environment. Hydrogen together with carbon responds to produce methane. The formation of methane bubbles in steel can lead to loss of fracture toughness and lead to intergranular cracking. The main challenge of this problem lies in early warning systems that can detect these bubble clusters before they reach the advanced stage. Several advanced ultrasonic inspections have been developed over the years due to the challenges of inspecting materials for defects and discontinuities. These cover time-of-flight diffraction (ToFD), phased array ultrasonic testing (PAUT), total focusing method (TFM), multi-mode total focusing method (MTFM), and others. However, these ultrasonic techniques used are typically used to detect all possible material defects. This paper briefly discusses the advantages and disadvantages of these techniques. MTFM has been successfully applied to characterize isolated or clustered signs, whether tilted or not, using high-frequency probes. The defects grouped in this paper are believed to be methane bubbles or HTHA. ToFD defect screening before aims to save time and money.

Keywords: clustered defects, ultrasonic testing (UT), high-temperature hydrogen attack (HTHA), time of flight diffraction (ToFD), phased array ultrasonic testing (PAUT), total focusing method (TFM), multi-mode total focusing method (MTFM)

INTRODUCTION

Equipment used in petrochemical plants that is made of carbon and low alloy steels is susceptible to high-temperature hydrogen attack (HTHA), which forces early component replacement and, on occasion, failure. The explosion at the Tesoro Anacortes Refinery in 2010 is a terrible illustration of how HTHA can occasionally cause catastrophic equipment failures and human casualties [1-4].

A common method for finding material faults and discontinuities is a non-destructive testing (NDT) [5]. NDT employs a variety of techniques, such as thermography, eddy current, x-radiography, and ultrasonics, to name a few. Each technique has benefits and drawbacks; occasionally, they are combined to maximize the likelihood of discovering a flaw [6]. None of the NDT methods are harmful to the object under investigation. The tested component can typically be used after the inspection (if no issues were detected), or occasionally even during the examination, because none of the NDT techniques harm the inspected material. One of the most used NDT techniques for finding, locating, and measuring faults in engineering materials under examination is ultrasonic testing (UT) [7][8]. UT is easy to use, identifies the defect's exact position, and generally has a high signal-to-noise ratio [9]. By creating and detecting mechanical vibrations or waves inside test objects, inspection is carried out [10]. There are numerous ways to accomplish this. The three common implementations are phased array systems (PA), time-of-flight-diffraction systems (ToFD), and pulse-echo systems (PE).

OBSTACLES TO IMPLEMENTING THE CURRENT APPLICATION

This section provides specifics on the primary components and configuration of a few chosen ultrasonic testing applications. Furthermore covered are the potential and difficulties of each application's implementation in a real-world setting for HTHA monitoring.

High-Temperature Hydrogen Attack (HTHA)

The interaction between the hydrogen that dissolves into the steel and the carbon that is either present as interstitial carbon or, more often, in carbides is known as HTHA [11]. Methane is created when carbon and hydrogen react. Due to its size, methane cannot diffuse out of the metal's main body. Instead, it accumulates at microstructural features including grain boundaries, inclusions, and free surfaces, where it precipitates as methane bubbles. Because methane bubbles are substantially bigger than hydrogen molecules and because their pressure in cavities can be up to two orders of magnitude higher [12]. These bubbles develop and combine until fissures, which usually take the form of intergranular failure, occur [13-14].

Damage from HTHA develops in 4 separate stages [2]. Methane-filled holes begin to build up along grain boundaries in stage one. The mechanical characteristics of the material deteriorate during stage 2 damage as a result of methane vacancies connecting and forming tiny fissures along the grain boundaries. Stage 3 entails the development of microfissures into macrofissures, which causes the component's structural integrity to rapidly deteriorate. By stage 4, larger cracks are formed as smaller fissures combine, and the structure is in serious danger of failing soon.

Ultrasonic Testing

The foundation of ultrasonic testing is the identification, localization, and measurement of faults utilizing the pertinent characteristics of ultrasonic waves. The pulse reflection method's guiding premise is as follows [15]: Transmitting and receiving are integrated functions of an ultrasonic probe. The ultrasonic transducer will receive some of the sound waves that were reflected in order to diminish ultrasonic echo through the coupling medium when the ultrasonic waves reach the workpiece's outer surface. This received signal is known as an echo signal. The other portion of the sound waves enter and travel through the workpiece, and the secondary echo is produced when the sound waves are transferred to the lower surface of the workpiece. At this point, the propagation time is given as t_1. After traveling through the upper surface of the workpiece and the coupling medium, this echo signal is picked up by the ultrasonic transducer, and the propagation time (t_2) is noted at this point. The thickness d of the workpiece can be calculated using Eq. 1 based on the sound wave velocity v, the sound wave propagation time difference and Δt, and the workpiece thickness [16]:

$$d = v\, x \frac{t_2 - t_1}{2} \tag{1}$$

where v is the rate at which sound waves move through the workpiece.

Conventional Pulse-Echo

Pulse-echo technique uses a transducer to both transmit and receive mechanical waves, as shown in Figure 1. The presence of pipeline walls or defects can cause reflections caused by sudden changes in acoustic impedance between two media (eg. steel and water). Analysis of the transit time between multiple reflected echoes can be used to measure pipeline thickness and identify defects better than laser scanning techniques [17]. The pulse-echo technique is reliable and makes a better test for measuring the thickness of the test object [18]. The three blue dots in Figure 1b not indicate a real void directly in the component. We need to place the probe on another side to imagine a whole defect.

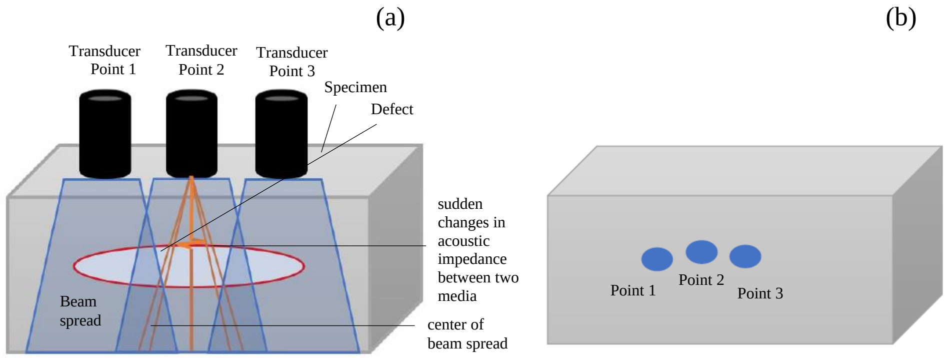

FIGURE 1. (a) Conventional pulse-echo setup; (b) Conventional pulse-echo inspection result (B-scan)

Time-of-flight-diffraction (ToFD)

On the same surface, two angle probes are arranged parallel so that an ultrasonic pulse produced by one transducer (emitter) is picked up by the opposing transducer (receiver) with precision [19]. The receiver normally picks up two waves: a Rayleigh wave that travels over the surface of the object being examined, and a second wave that is reflected off the back wall (compression or longitudinal wave). As the longitudinal wave propagates, as seen in Figure 2, a diffraction pattern is produced when the ultrasonic beam encounters an interior discontinuity. It is feasible to confirm the existence of discontinuities through the detection of diffracted waves. Trigonometry can be used to calculate the depth of one discontinuity and then properly evaluate it when determining the pulse's period of flight. The time of flight of the diffracted waves is used to calculate the size and virtual location of the discontinuity.

The height of the flaw may be accurately determined using the ToFD approach. ToFD is an effective method for locating discontinuities. Due to the fluctuation in the probe centering space (PCS) and the number of pieces that ToFD requires, it also takes longer to execute ToFD than pulse-echo.

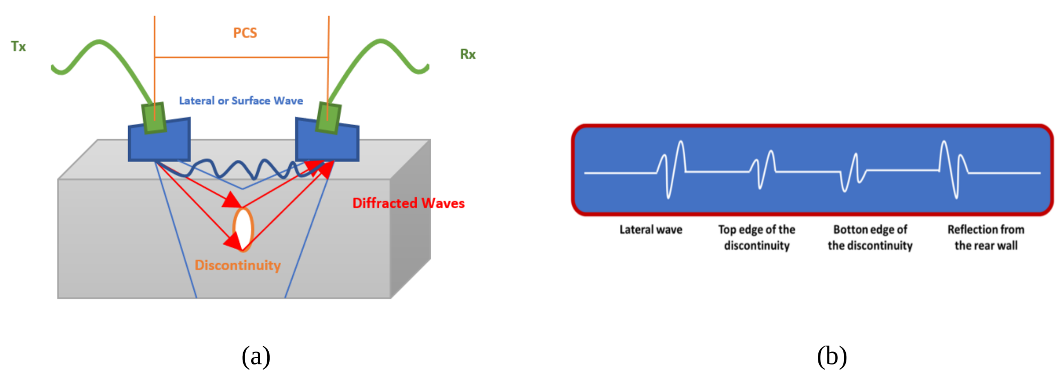

FIGURE 2. (a) Diffraction and specular waves are shown schematically. Rx is the receive transducer, and Tx is the transmit transducer; (b) A-scan readings for time-of-flight diffraction diagram.

Phased Array System (PA)

Using the principle of time-delayed triggering of the transmitting transducer elements and time-corrected reception of the detected signals, a phased array system (PA) is a multi-channel ultrasonic system [20]. The fundamental benefit of the phased array over other UT probe types is the ability to simultaneously inspect the material from a variety of angles using modifications in angle control, focussing, and aperture control, as shown in Figure 3. Figure 3 details the basic working principles of phased array, including angle control, electronic focusing, and aperture control. A phased array transducer is a 1-D rectangular group of individual elements, each having its own pulser and receiver circuitry. All elements are connected to, and controlled by, a computerized ultrasound system. The system is able to activate each element independently. By timing, or phasing the individual elements appropriately, a cylindrically converging wavefront can be created as shown in Figure 3b. This is analogous to the phase delays caused by the mechanical lens placed on the front of a single-element transducer. Using a different phase pattern, a different focal point can be achieved. Additionally, a linear phase pattern will cause an unfocused beam to be steered off the axis of the transducer as shown in Figure 3a. We can also use a subset of elements and create a smaller aperture with a bigger opening angle as shown in figure 3c.

Unfortunately, conventional PA restricts the profile reconstruction and qualitative fault diagnosis by only using the scattered waves from flaw tips [21]. Even in materials with high levels of grain noise, where traditional transducers like ToFD find it challenging to identify the tip from the background scattering, the diffraction tip can be detected by producing a focussed beam. Moreover, PA has the benefit of functioning in pulse-echo, which makes the mechanical setup simpler, especially for samples of smaller sizes. The biggest drawback of PA for crack evaluation is that, aside from the tip, the majority of the crack behaves like a specular reflector, creating a substantial echo only when the beam direction is perpendicular to the fracture path. The result is that typically, only a single sector image may be used to follow the crack propagation pattern in all of its extension (S-Scan) [22].

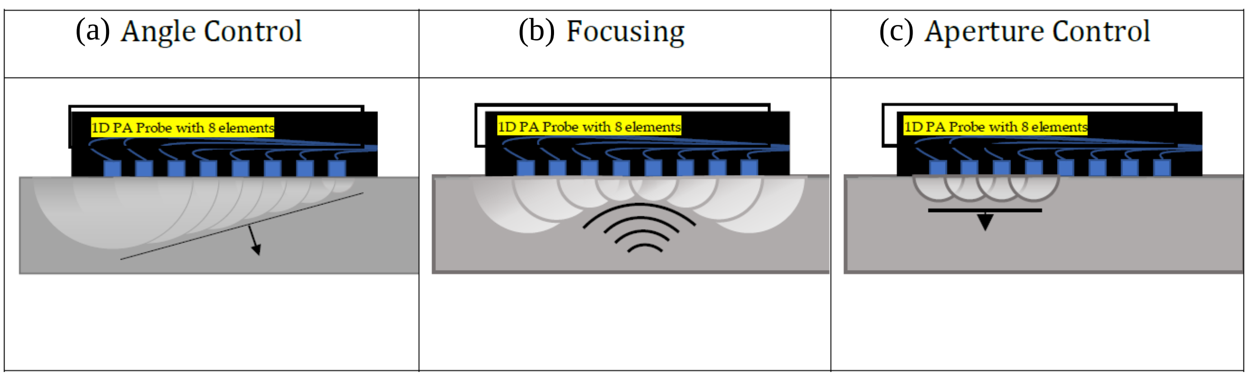

FIGURE 3. Rules of basic phased array focals: (a) angle control; (b) focusing; and (c) aperture control

Total Focusing Method (TFM)

By using just one element for emission and each element independently for reception, the Total Focusing Method (TFM) gets around PA's beam-directivity restriction [22]. using a different emitting element. The collection of low-resolution images are averaged to provide a high-resolution image dynamically focused on emission and reception, which might be thought of as the benchmark for delay and sum (DAS) beamformers when all of the array elements have been employed as emitters. DAS performs time delay calculations based on the geometry of the sensor array and the conditioning phase of the signal by delaying the arrival time of the signal detected by each element of the sensor array. The result is an amplification of the periodic guided ultrasound component along the spatial domain and a relative reduction in the level of the random noise component of the raw signal [23]. Full Matrix Capture (FMC) refers to the collection of all signals that were acquired throughout the procedure. Following the collection of FMC data, each picture pixel is subjected to synthetic focusing at (x, z) to produce an array image which is written in Equation (2):

$$I(x, z)\ [24]: (x, z) = \left| \sum h_{tx,rx} \left(\frac{\left| \sqrt{(x_{tx}-x)^2+z^2} + \sqrt{(x_{rx}-x)^2+z^2} \right|}{c} \right) \right| \quad (2)$$

For all t_x and r_x, where c is the speed of the incident wave and h_{tx},r_x (t) is the recorded ultrasonic response at a specific time instance t at a receiver point at (x_{rx}, 0) when an excitation is performed with a transmitter at (x_{tx}, 0). All feasible transmitter-receiver combinations are taken into account when computing the total pixel intensity I (x,z). Here, the presence of a defect is directly correlated with the pixel intensity of the picture I at a certain place (x,z). Wave diffraction places a cap on the imaging resolution that the TFM can produce. The feasible imaging resolution, L_R, of the TFM at the imaging point at (0, z), as determined by the Rayleigh criterion [25], the achievable imaging resolution L_R of the TFM at the (0,z) imaging point is given by Eq. (3). Where the angle shown by Θ in Figure 4 and λ is the angle of the incident wave. The ultrasonic array's arrangement determines Θ at a specific imaging location. L_R is of the order of and cannot be less than 0.61, according to Eq. (3):

$$L_R = \frac{0.61\lambda}{\sin\theta} \quad (3)$$

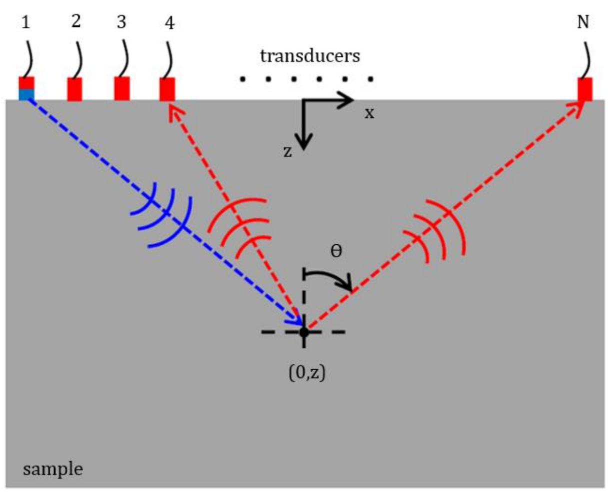

FIGURE 4. Diagram of full matrix capture (FMC). Excitation transducers are represented by the blue transducers, whereas sensing transducers are represented by the red transducers.

Full matrix capture (FMC)-based post-processing methods have been developed to characterize faults with significant impact [26]. Using techniques like synthetic aperture focusing technique (SAFT), the delay and sum (DAS) beamforming strategy, for example, improves resolution and signal-to-noise ratio (SNR) by focusing on each pixel in the region of interest (ROI) [27][28] and total focusing (TFM) improve ROI [28][29][24]. The TFM technique is shown schematically in Figure 5. High frame rate is required when generating images in real-time by taking repeated shots, because a separate shot is required for each point of the target. However, in combination with FMC, this can be greatly accelerated. TFM proceeds by first discretizing the spatial region in front of the array into a raster. The extent of the raster is limited only by the maximum individual A-scan times. The beam can then be focused on each point in the grid to produce a perfectly focused image.

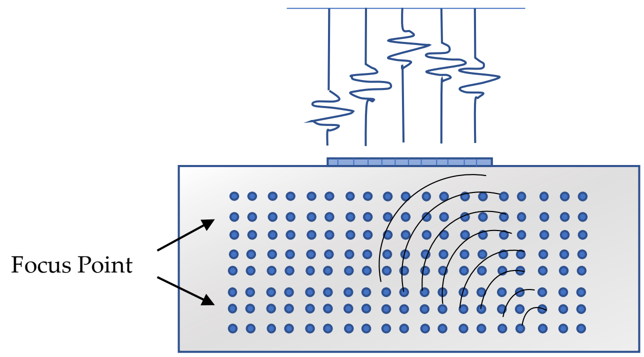

FIGURE 5. Total focusing method (TFM)

Multi-Mode Total Focusing Method (MTFM)

Volumetric and crack-like defects can be distinguished using Multimode Total Focusing (MTFM), according to research [30]. MTFM was developed to represent fault profiles using reflected waves from fault planes [22]. MTFM's modes can be divided into direct, half-skip, and full-skip modes based on the sample's bottom reflection time, as seen in Figure 6. There are 21 views, each one representing a unique ray path or wave mode. For describing particular regular fracture profiles, proper view determination is crucial, and this has been extended to 3D imaging [31]. However, due to the volume and complexity of data analysis, reliable human analysis of multiview images to enhance detection may be impractical and unreliable. For instance, a scan of a butt weld on a pipe with a diameter of 12 inches at a scan distance of 1 mm will yield 1000 records. According to the direct, half-skip, and full-skip modes, each data set can produce 21 multiview images, which could need the operator viewing 21,000 images for each weld [32] Therefore, discontinuity identification by ToFD is required in advance.

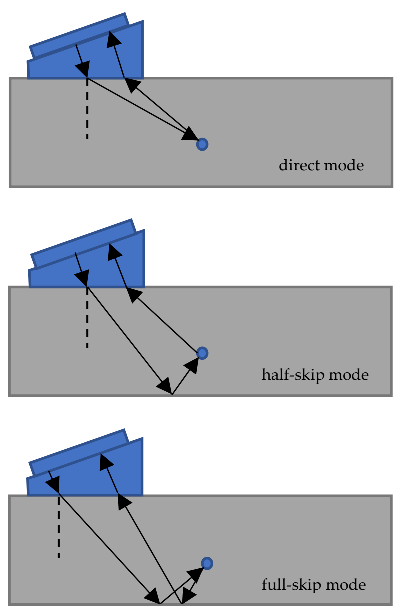

FIGURE 6. Schematic diagrams of propagation paths in direct mode, half-skip mode, and full-skip mode

After briefly introducing the development of ultrasonic testing for defect detection, Table 1 summarizes the advantages and disadvantages of each method.

TABLE 1. Summary of the recent ultrasonic testing detection technique

No.	Technique	Strength	Weakness	Ref.
1	Conventional Pulse Echo	- better test to measure the thickness of a testing object	- pulse-echo did not execute the flaw dimensioning any better than ToFD did.	[18]
2	ToFD	- determine the height of the defect properly, so ToFD is good for identification discontinuity screening - ToFD takes less time than PAUT	- execution takes longer than pulse-echo because of the PCS variation and the number of components that ToFD requires.	[18][32]
3	Phased Array (PAUT)	- more flexible and reliable than Conventional Pulse-Echo - picture diffraction tips that are highly sensitive and detailed	- only when the beam direction is perpendicular to the fracture channel, the majority of the crack acts as a specular reflector and produces a discernible echo. - restricting the profile reconstruction and qualitative identification of defects	[21], [32], [33], [34]
4	TFM	- accurately measure flaws that are larger than a few times the wavelength - generating superior image resolution relative to conventional PAUT imaging methods	- The diffraction limit makes it difficult to characterize tiny flaws. - Execution time is greater than phased array because the time is taken to fire a differently formed beam to focus at every inspection region.	[34], [35], , [36], [37]
5	MTFM	- volumetric and crack-like defects can be distinguished by comparing their image amplitudes in the MTFM algorithm - indicate one or more defects	- due to the quantity and complexity of the data that needs to be evaluated, execution time is longer than TFM. - understanding all inspection parameters is necessary for successful imaging and correct co-registration of multimode images. - array position corresponding to the ultrasonic velocities and specimen thickness.	[38], [32]

CONCLUSION

MTFM was developed to discriminate between volumetric and crack-like faults and to identify one or more problems. The MTFM images created from both simulated and experimentally observed FMC data sets reveal that the presence of a certain type of defect is usually visible in some or all of the views with varying image amplitudes. The amplitude discrepancies between views can be utilized to classify the fault type [32] .

Due to its size, HTHA is unable to diffuse out of the metal's core and instead concentrates at microstructural features such grain boundaries, inclusions, and exposed surfaces, where it precipitates as methane-filled bubbles. Using MTFM, it is possible to identify and view these methane-filled volume defects. To achieve adequate picture resolution, Equation 3 suggests using a high frequency probe. The most advanced phased array technology currently available uses a probe frequency of 10 MHz [39]. Furthermore, it can also be seen the direction of crack growth, the size of the bubble, and its location. However, MTFM has its drawbacks regarding duration. Therefore, a ToFD is needed to indicate discontinuities in the material for time efficiency.

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