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Ultrasonic TOFD Testing Model for Crack Measurement in Thick Wall Weldment

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Abstract

In this paper, both forward and inverse problem about crack testing by using ultrasonic Time of Flight Diffraction (TOFD) B-scan mode are studied. For forward problem, the propagation behavior of ultrasonic beam is described, and the electrical and electromechanical elements of inspective system are characterized by system efficiency factor. Based on this, crack simulating model is established by employing Kirchhoff approximation theory. By using the model, ultrasonic TOFD A-scan line is simulated and B-scan foreground image is synthesized. For inverse problem, in order to obtain lateral location and buried depth information of crack in the weld, B-scan image reconstruction is studied. According to the dynamic relation between the probes and crack tip in the course of testing, synthetic aperture focusing (SAF) algorithm for image enhancement is developed. The results show that the simulated dada are in better accordance with the measured ones and the presented SAF algorithm can be validated by the simulating model. Processed by SAF, high resolution image can be obtained by using transducers with poor sound directivity and lower frequency, and measurement can be carried out rapidly with high accuracy.

Keyword: Model, Ultrasonic TOFD, SAF, Weld crack

1. Introduction

Weld crack with acute break, is the most dangerous in thick wall weld components. Ultrasonic TOFD is a recently developed technique that relying on measures the time differences from signals diffracted by the extremities of planar defects. The technique can be set up and operated quickly. Analysis can be performed immediately from the digital images and data are available for additional post test reviews[1].

Though ultrasonic TOFD is accepted as the most suitable method for measurement of crack-like defect, it has technological limitations. One problem that ultrasonic TOFD suffers from is that the diffracted defects signal responses are exaggerated in length as a consequence of being scanned across by the wide beam envelope in B-scan mode. SAF has been adopted from radar applications where one wanted to improve the lateral resolution in airborne radar mapping systems. It is a technique where the focusing is performed by software after the data collection already has been performed and is used in ultrasonic image reconstruction[2,3].

In many practical situations, flaw signals were acquired together with non-relevant signals caused by noise, lateral wave and back wall echo. Meanwhile, the system error effects on testing result very much. As a consequence, the interpretation of rationality of SAF algorithm becomes a difficult task. In order to verify SAF algorithm, it is desired to have an effective way to receive ideal testing result without system error. Prediction is a good way for tackle the problem. Until now, extensive research has been carried out develop models to predict the UT signals. Several models have been proposed that can predict ultrasonic flaw signals in a very computationally efficient manner[4].

In this paper, ultrasonic TOFD A-scan signals and B-scan image of a bottom surface broken crack are simulated by adopting the multi-Gaussian beam model and Kirchhoff approximation theory. SAF algorithm is applied on the simulated B-scan image to verify its validity. At last, B-scan image of a real weld crack is obtained and measurement is carried on the SAF processed image.

2. Ultrasonic TOFD testing model

This part proposes an approach to modeling ultrasonic TOFD testing that can predict A-scan signal as well as B-scan image from a bottom surface broken crack.

In ultrasonic TOFD testing mode, the transmitting probe radiates ultrasonic beam into the solid wedge, and the bounded beam transmits the water coupled interface between the wedge and the specimen and then propagates into the solid specimen with certain refracting angle. When the incident beam reaches the tip of the bottom surface broken crack, a diffractive beam is generated and propagates with a broad angle scope. The diffractive beam propagates through the interface between the specimen and the wedge of receiving probe. Here, only the defect diffractive signal is concerned and non-defect signal, such as lateral wave and back-wall wave are ignored. So, the modeling task aims at the physical analysis of ultrasound propagation in solid and the interaction of ultrasound with crack tip.

2.1 Multi-Gaussian beam model

Modeling the fields radiated by ultrasonic transducers is a particularly challenging task because of the large number of possible transducer types, sizes, and configurations that are used in practice. The ultrasonic TOFD beam field emitted by transmitter around the flaw is calculated with multi-Gaussian beam model. For a circular piston transducer having a uniform velocity, v_0 on the face, the ultrasonic pressure field at point x can be formulated as[4]:

$$\begin{aligned}\frac{-i\omega u^{p}\left(x_1,x_2,x_3\right)}{v_0}&=\frac{P_0}{\rho_1 c_1 v_0}T\exp\left(ik_1 D+k_2^{p}x_3\right)\frac{\sqrt{\det G_1^{P}\left(0\right)}}{\sqrt{\det G_1^{P}\left(D\right)}}\\&\quad\times\frac{\sqrt{\det G_2^{p}\left(0\right)}}{\sqrt{\det G_2^{p}\left(x_3\right)}}\exp\left(\frac{ik_1 x^{T}\left[G_2^{p}\left(x_3\right)\right]^{-1}x}{2}\right)\end{aligned}\tag{1}$$

$$\begin{aligned}\frac{-i\omega u^{p}\left(x_1,x_2,x_3\right)}{v_0}&=\sum_{n=1}^{15}\frac{A_n}{1+\left(iB_n D/x_r\right)}T\exp\left(ik_1 D+k_2^{p}x_3\right)\\&\quad\times\frac{\sqrt{\det G_2^{p}\left(0\right)}}{\sqrt{\det G_2^{p}\left(x_3\right)}}\exp\left(\frac{ik_1 x^{T}\left[G_2^{p}\left(x_3\right)\right]^{-1}x}{2}\right)\end{aligned}\tag{2}$$

The scattered waves from the flaw are evaluated via the Kirchhoff approximation. In order to calculate scatter wave field around the crack tip, traditional Kirchhoff approximation theory is corrected.

2.2 System efficiency factor

The system efficiency factor, $\beta(\omega)$, introduced by Thompson and Gray, is an important parameters that can describe the characteristics of the complete ultrasonic measurement system including the electrical and electromechanical elements of inspective system. $\beta(\omega)$ can be computed by the de-convolution of an experimental signal obtained from a reference reflector by a corresponding theoretical reference reflector model, as given by Eq.(3) [5].

$$\beta(\omega)=\frac{V_{ref}(\omega)}{[v_r/v_0]_{ref}}W(\omega) \tag{3}$$

$\beta(\omega)$ is calculated by using the reference signal shown in Fig.1. The signal is back-wall echo received by testing an aluminum plate of 20mm in thickness with ultrasonic pitch-catch mode. The calculated $\beta(\omega)$ is shown in Fig.2. Once the system efficiency factor is defined, the time domain waveforms to be acquired experimentally from various targets can be predicted by the inverse Fourier transform of the ultrasonic testing models.

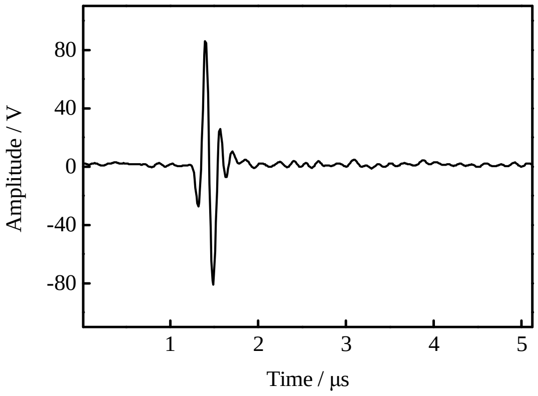


Fig.1 Reference signal

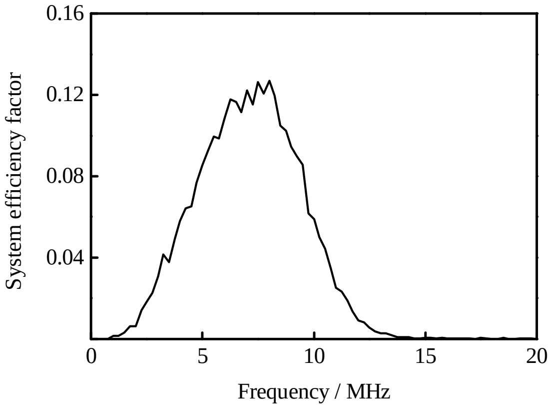


Fig.2 System efficiency factor

2.3 Simulating result

Electro discharge machining (EMD) slots of different size, which represents bottom broken weld cracks, are fabricated in weld-free aluminum specimen of 20mm in thickness. Ultrasonic TOFD A-scan line and B-scan are obtained by testing the artificial defect. By employing Multi-Gaussian beam model, and Kirchhoff approximation theory, artificial crack tested A-scan lined is simulated, as shown in Fig.3.

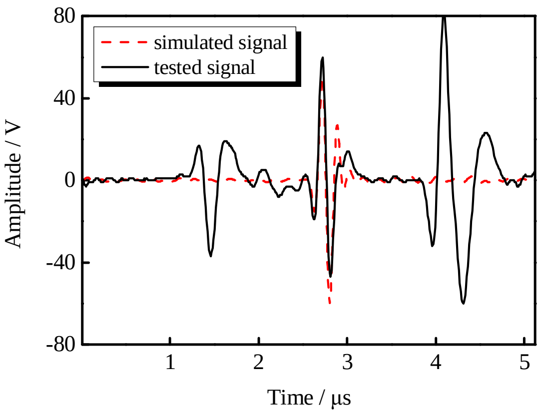
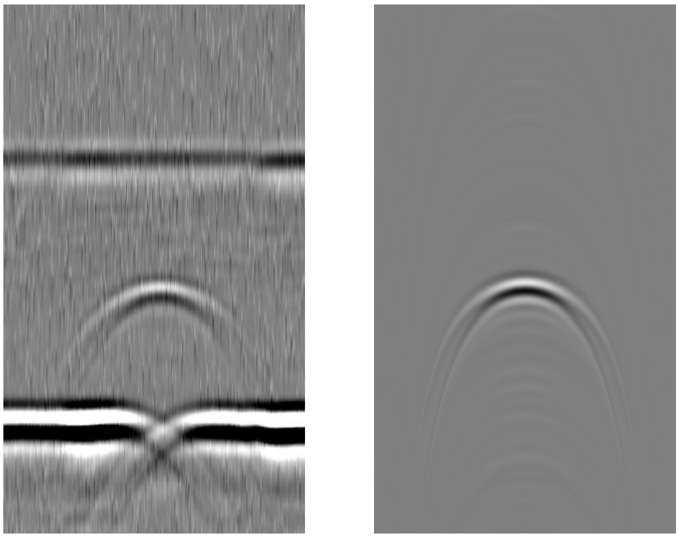


Fig.3 Simulation of A-scan line

Lateral wave and back-wall echo are redundant data in the simulation though they are very important for calibration defect in the tested image. Only crack tip diffractive wave is simulated. Through collecting every simulated A-scan line in the course of B-scan, the foreground image is synthesized. Fig.4 shows are tested and simulated B-scan image of the artificial defect, respectively.



a) Tested image b) Simulated image

Fig.4 Simulation of B-scan image

4. Model validates SAF algorithm

SAF technique allows for dynamic focusing using much simpler hardware. The technique can also be applied to measurements from B-scan systems in directions where there is no electronic focusing or to improve focusing for testing systems without ability to perform dynamic focusing. The algorithm mainly includes time-shift operation and sum-average calculation.

To use the technique A-scan lines in the tested image should be calculated one by one. Firstly, we assume the A-scan line to be analyzed contains true depth and lateral location message of crack tip in the specimen. Then according to the arriving time of defect wave in the A-scan line being analyzed, the corresponding delay time of defect wave in adjacent A-scan lines are calculated When SAF correlation is conducted, A-scan lines adjacent to the one being analyzed are time-shifted according to the calculated retardation, and then the amplitude of time-shifted A-scan lines are summed up and averaged. This correlation is obtained by the summation over the adjacent lines as follow:

$$X_n(T_n) = 1/(N+1)\sum_{j=n-N/2}^{n+N/2} X_j(T_j - \Delta T_j) \qquad (4)$$

where $X_n(T_n)$ is SAF processed A-scan signal X_n; N the total number of adjacent A-scan lines to the one being analyzed; $X_j(T_j - \Delta T_j)$ time-shifted jth A-scan line, and ΔT_j the corresponding time-shifted quantity.

If the assumption is correct, the sum-average result in an enhanced response; if wrong, there is a poor correlation or zero. The principle of SAF can be illustrated as Fig.5. Apply the described algorithm to the simulated image that shown in Fig.4 b) and the reconstructed image is shown in Fig.6. The highlight point in the processed image presents the location of the crack tip in the specimen.

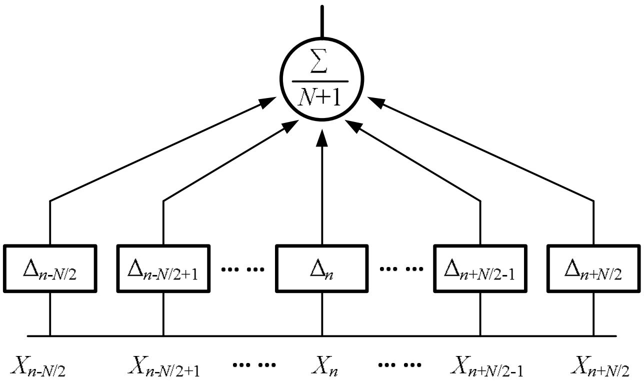
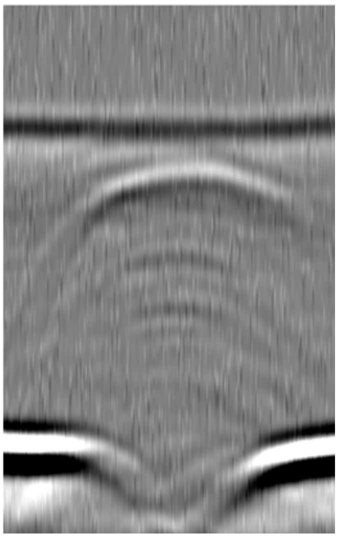


Fig.5 Schematic of SAF processing

Fig.6 SAF processed simulated image

5. Measured result of weld crack

In this paper, the fatigue crack in each weld specimen was propagated along and through the weld under cyclically loading in 3-point bending. Ultrasonic B-scan is conducted on the opposite side wall to the crack. A typical B-scan image is shown as Fig.7 a), and its ultimate processed image obtained by using SAF is shown as Fig.7 b).



a) Raw image b) SAF processed image

Fig.7 Processing result of image of weld crack

The measured location of the crack tip in images before and after processing are compare with the destructive measuring results, see in Fig.8. The horizontal axis in the plot corresponds to the scanning surface, and the zero of the horizontal coordinate which is set beforehand represents the midpoint of B-scan path. The vertical axis represents the buried depth of the tips from scanning surface in the specimen. The measured and actual locations of the tips are shown in the corresponding plots, in which the measurement errors in raw and ultimately processed image are compared. Five measurements are taken on the original images, and the data from ultimately processed image is obtained by one measurement.

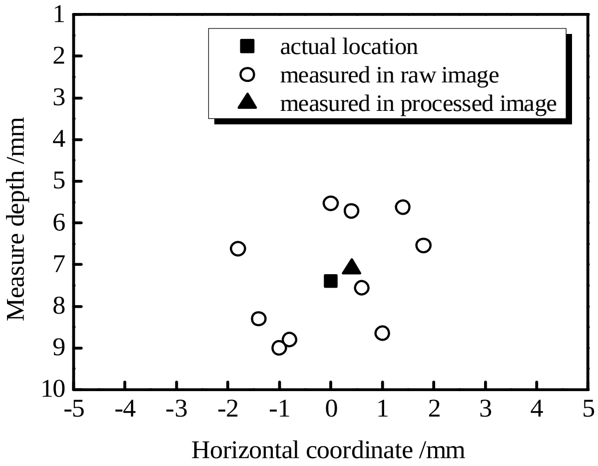


Fig.8 Measuring results of weld crack tip

6. Conclusions

(1) In this paper, forward problem of ultrasonic TOFD imaging is studied and B-scan testing results are simulated. The experimental results show that the simulated dada are in better accordance with the measured ones.

(2) SAF algorithm is developed and applied in the improving lateral resolution of ultrasonic TOFD B-scan image. Forward synthesis can validate SAF algorithm and do help to solve inverse problem of non-destructive characterization.

(3) In the ultimately processed image, buried depth and lateral location of crack tip can be identified within an error of 0.5mm. Measurement taken on ultimately processed image is more rapidly with higher accuracy than raw image.

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