MODEL-BASED ENHANCEMENT OF THE TIFD FOR FLAW SIGNAL IDENTIFICATION IN ULTRASONIC TESTING OF WELDED JOINTS

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ABSTRACT. Flaw signal identification of ultrasonic testing is usually carried out prior to the quantitative evaluation of flaws for classification and sizing. In many practical inspection of welded joints, it becomes a truly difficult task due to the presence of non-relevant indications caused by various geometric reflectors. To overcome such a difficulty, the TIFD (Technique for Identification of Flaw signals using Deconvolution) has been proposed previously. In the present work, model-based enhancement of the TIFD is considered for the convenience of practical application. The current, enhanced approach adopts only one reference signal which is the reflection from the circular part of the STB-A1 block. Deconvolution patterns for the geometric reflections and flaw signals are predicted by use of theoretical ultrasonic testing models. The deconvolution patterns are strongly dependent on the type of the flaws, and are useful for the screening of flaw signals from the non-relevant indications caused by geometric reflections.

INTRODUCTION

Angle beam ultrasonic testing is widely used for inspection of welded joints. In many practical situations flaw signals are acquired together with non-relevant signals caused by geometrical reflectors such as corners, counter bores and weld roots [1]. In general, the geometric reflection signals can be discriminated from the flaw signals based on beforehand information on the testing location and the geometry of welded joints. Echo-dynamic patterns of the scanning transducer around the indication can also be used for the identification of flaw signals. However, the traditional methods have ambiguity since the decision is based on the subjective experience and knowledge of inspectors. B- and C-Scan obtained by an automated ultrasonic testing system can provide information on the identification of flaw signals [2]. However, those usually require expensive equipments and the identification of flaw signals is possible only after the scanning. Moreover, the discrimination will be very difficult if the geometry is complex.

To overcome these difficulties, the TIFD (Technique for Identification of Flaw signals using Deconvolution) has been proposed previously [3]. The TIFD identifies flaw signals using a similarity function defined from the deconvolution of a target signal by a reference signal. The TIFD showed great potential to identify various practical signals, especially to distinguish notch signals from the geometric reflections. The TIFD proposed
in the previous work [3] requires many reference signals of which the number is the same as that of the flaw types under consideration. However, it will be very difficult to acquire various reference signals in many situations. Therefore, there is some limitation to implement the TIFD to the practical applications.

In the present work, we propose a model-based TIFD which is an enhanced version of the previous one in order to relax the requirement of acquiring various kinds of reference signals. The enhanced approach adopts only one reference signal obtained from the circular part of the STB-A1 block. In the present study, to demonstrate the feasibility of the enhanced approach, four kinds of flaws are considered; a corner and a counter bore as geometric reflectors, and a crack tip and a spherical void as flaws. The time-domain waveforms and deconvolution patterns are predicted using ultrasonic testing models. It was found that the deconvolution patterns of the geometric reflection are impulse-like patterns, whereas those of flaws are bipolar patterns. Therefore, the deconvolution patterns obtained by the model-based TIFD can serve as the criteria of flaw signal identification.

THE ENHANCED TIFD: MODEL-BASED

The basic concepts and details of the initial TIFD were described in reference [3], and only very brief description is given here to merely provide the necessary information for our discussion. Let $f(t)$ and $g(t)$ be a reference and target signal, respectively. Then, the deconvolution pattern which was called the similarity function in the previous work [3], $h(t)$ can be expressed as

$$h(t) = f(t) * g^{-1}(t)$$

where, $*^{-1}$ denotes the deconvolution. Basic idea of the initial TIFD is shown in Fig. 1. When reference and target signals are similar, the deconvolution pattern becomes a sharp impulse-like shape, otherwise it becomes complicated shape. Thus, it is possible to decide the type of the flaw under consideration based on the shape of the deconvolution pattern.

The major limitation of the previous, initial TIFD is that it requires defining various kinds of reference signals experimentally which is quite often impractical. To overcome such a limitation, here we propose a model-based, enhanced TIFD which adopts only one reference signal. In the present work, the signal obtained from the STB-A1 block was chosen as a well-defined reference signal. Then four kinds of targets, such as a counter bore, a corner, a circular crack and a spherical void, were considered for the feasibility study on the current TIFD approach.

[FIGURE 1. A schematic representation of the TIFD.]
As shown Fig. 2, if target signals are deconvolved by the reference signal, we can acquire the four different deconvolution patterns. The characteristics of these deconvolution patterns would be quite different from those of the initial approach. Fortunately, however, these characteristics can be predicted by use of theoretical ultrasonic testing models.

For this prediction, the receiving signals from targets were firstly calculated using angle beam ultrasonic testing models. Then, the deconvolution patterns were predicted from the calculated signals.

RESULTS AND DISCUSSION

Reference Signal

In practical field inspection, ultrasonic transducers are usually calibrated by use of the reflection signal from the circular part of the STB-A1 block as shown in Fig. 3 (a). This signal can also be used for reference signal of the enhanced TIFD. Fig. 3 (b) shows an experimentally measured reflection signal from the circular part of the STB-A1 block. This signal was used for the calculation of the system efficiency factor [4], which is one of the key ingredients for the prediction of ultrasonic testing signals using ultrasonic measurement models [5].

FIGURE 2. A schematic representation of the enhanced TIFD.

FIGURE 3. (a) Geometrical setup for the calibration of an angle beam ultrasonic transducer and (b) the experimental reference reflection signal obtained by a 45 degree angle beam transducer (5 MHz center frequency, 0.375 inch diameter).
**Ultrasonic Testing Models**

Ultrasonic testing signals from geometrical reflectors and various flaws can be calculated using the ultrasonic measurement models [5]. The measurement models involve four ingredients: 1) the system efficiency factor, 2) the radiation beam field from a transducer, 3) the scattering field from a flaw, and 4) the reception by a receiving transducer. To predict angle beam, pulse-echo ultrasonic testing signals, Kim and Song [4] has developed ultrasonic measurement models based on the multi-Gaussian beam model [6] and the Kirchhoff approximation[7] for the radiation beam field and the scattering amplitude from a flaw, respectively. In the present work, two kinds of geometric reflectors (a counter bore and a corner) and two kinds of flaws (a circular crack and a spherical void) were considered as the targets to be identified. The ultrasonic measurement models to predict ultrasonic testing signals for four targets can be expressed as follows:

Reflection from a counter bore:

\[ V_{cb}(\omega) = \frac{B(\omega)}{S} \int_{S} v_{cb}(\omega, x) dS \]  \hspace{1cm} (2)

\[ v_{cb}(\omega, x) = \sum_{m=1}^{15} \frac{A_m}{iB_{x1}} \left( \frac{R_{12}^{(m)}}{R_{23}^{(m)}} \right)^{2} T_{21}^{(m)} \sqrt{\det G_{1}^{(m)}(0)} \sqrt{\det G_{2}^{(m)}(0)} \sqrt{\det G_{4}^{(m)}(0)} \sqrt{\det G_{4}^{(m)}(z_1)} \sqrt{\det G_{4}^{(m)}(z_2)} \sqrt{\det G_{4}^{(m)}(z_4)} \exp(2ik_{1}z_1) \exp(2ik_{2}z_2) \exp \left( \frac{ik_{4}^{2} \Phi^{(m)}(z_4)}{2} \right) \]  \hspace{1cm} (3)

Reflection from a corner:

\[ V_{co}(\omega) = \frac{B(\omega)}{S} \int_{S} v_{co}(\omega, x) dS \]  \hspace{1cm} (4)

\[ v_{co}(\omega, x) = \sum_{m=1}^{15} \frac{A_m}{iB_{x1}} \left( \frac{R_{12}^{(m)}}{R_{23}^{(m)}} \right)^{2} T_{21}^{(m)} \sqrt{\det G_{1}^{(m)}(0)} \sqrt{\det G_{2}^{(m)}(0)} \sqrt{\det G_{4}^{(m)}(0)} \sqrt{\det G_{4}^{(m)}(z_1)} \sqrt{\det G_{4}^{(m)}(z_2)} \sqrt{\det G_{4}^{(m)}(z_4)} \exp(2ik_{1}z_1) \exp(2ik_{2}z_2) \exp \left( \frac{ik_{4}^{2} \Phi^{(m)}(z_4)}{2} \right) \]  \hspace{1cm} (5)

Scattering from a circular crack and a spherical void:

\[ V(\omega) = B(\omega) \exp(2ikH_{1}) \exp(2ik^{2}H_{2}^{\frac{1}{2}}) C(\omega) \frac{A(\omega) - c_{S}^{2}}{-i \omega \rho_{2}} \frac{c_{S}^{2}}{\rho_{1} c_{1}} \]  \hspace{1cm} (6)

\[ C(\omega) = \sum_{m=1}^{15} d^{(m)} \frac{A_{m}}{iB_{x1}} \left( \frac{R_{12}^{(m)}}{R_{23}^{(m)}} \right)^{2} \sqrt{\det G_{4}^{(m)}(0)} \exp \left[ ikx^{2} \left( \frac{G_{4}^{(m)}(H_{2})}{2} \right)^{\frac{1}{2}} \left( \frac{H_{2}}{H_{1}} \right)^{\frac{1}{2}} \right] \]  \hspace{1cm} (7)

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where, \( \omega \) is the angular frequency, \( S \) is the transducer area, \( \beta(\omega) \) is the system efficiency factor, \( A_n \) and \( B_n \) are height and width factors of individual Gaussian beams, \( \rho_1 \) and \( \rho_2 \) are densities of the wedge and the steel, \( c_1 \) and \( c_2 \) are the longitudinal wave velocity in the wedge and the shear wave velocity in the steel, \( A(\omega) \) is the far-field scattering amplitudes form circular crack and spherical void, and \( z_r \) is the Rayleigh distance. The definitions of the other terms can be found in references [4] and [6].

**Prediction of Time Domain Waveforms**

Figure 4 shows the calculated time-domain waveforms (using the Eqs. (2), (4) and (6)) for four targets by use of a 45 degree angle beam transducer of 5 MHz center frequency and 0.375 inch diameter. Here, it should be noticed that the crack tip signal (in Fig. 4(c)) was taken as the first group of the circular crack signal. Since, the crack tip signal could not be calculated accurately by the Kirchhoff approximation.

**Prediction of the Deconvolution Patterns**

Figure 5 shows the calculated result of deconvolution patterns for four flaw signals (as shown Fig. 4) by adopting the specular reflection from the circular part of the STB-A1 block (as shown in Fig. 3(b)) as the reference signal. The time domain waveforms as shown in Fig. 4 can not be distinguished from each other, however, the deconvolution patterns shown in Fig. 5 can be clearly distinguished even with a naked eye. As shown in Fig. 5 (a) the deconvolution of the counter bore reflection signal shows the positive "impulse-like pattern", while that of a corner reflection signal does the negative "impulse-like pattern" (Fig. 5(b)). On the other hand, the deconvolution patterns of scattering signal from a circular crack and a spherical void show "bipolar patterns," as shown in Fig. 5 (c) and (d).

![FIGURE 4. Calculated time domain waveforms for (a) a counter bore, (b) a corner, (c) a crack tip, and (d) a spherical void.](image-url)
FIGURE 5. Deconvolution patterns of calculated signals for (a) a counter bore, (b) right at a corner, (c) a circular crack, and (d) a spherical void.

From these results, it can be found that the deconvolution patterns are dependent on the scattering mechanism. The impulse-like patterns are due to the simple reflection (for example, for counter bores and corners) and the bipolar patterns are due to the scattering from small flaws (for example, crack tips and spherical voids). Therefore, deconvolution patterns can be used as a robust criterion for the discrimination of flaw signals from geometrical reflections.

CONCLUSIONS

In the present work, we have introduced a model-based, enhanced TIFD which adopts only one well-defined, single reference signal. The deconvolution patterns of four kinds of targets (a counter bore, a corner, a crack tip and a spherical void) has been investigated by use of angle beam ultrasonic testing models, and it has been found that their characteristics are strongly dependent on the nature of scattering mechanism. The simply reflected signals generated from geometric reflectors (such as a counter bore and a corner) produce the impulse-like deconvolution patterns. While, the scattered signal from small flaws (such as a crack tip and a spherical void) give the bipolar patterns. Thus, based on the characteristics of convolution patterns, one can easily distinguish flaw signals form the geometric reflection. The experimental validation of the model-based TIFD result will be reported shortly.

REFERENCES

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