An accurate real-time immersion method for automatic ultrasonic measurement of thin-wall hot-rolled structural carbon steel

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1. Introduction

Thickness measurement of vessels is a maintenance requirement for lifetime assessment of corrosion. The key idea concept for determining thickness without damaging or contacting the materials is called ultrasonic thickness measurement (UTM) [1–3]. UTM is recognized as a highly promising technique for detection; however, the interpretation of results by an A-scan is strongly dependent on the skill and experience of the operator who requires extensive training. The A-scan result presents a series of received ultrasonic energy measurements as a function of time and acquired as a linear representation of echo amplitude along a single line of sight. In the A-scan, comparative discontinuity size can be estimated by the amplitude comparison recorded from reflectors. This problem is further complicated in the case of thin walled vessels since superposition of multi waves is possible, including an initial pulse and both longitudinal and transverse waves of reflected surface echoes which appear at the transducer and surface interface. This leads to ambiguity in signal processing because the bottom surface echo is concealed. To satisfy this weak point, the distance between the probe and specimen is adjusted to separate the initial pulse and echoes. In immersion ultrasonic testing, both the ultrasonic transducer and the specimen are immersed in the couplant (water). Using a coupling makes it feasible to maintain consistency while manipulating the probe and the test specimen. The adjusted distance is known allowing correct measurement of traveling time; however, in real applications, this distance cannot be obtained simultaneously with the thickness measurement.

Here, a concept is proposed to automatically measure thin-walled hot-rolled structural steel for oil and gas reservoirs by installing a robot inspector. The method is performed using a combination of both Hilbert transform and zero-crossing (HTZC) methods. The Hilbert transform serves as an analytical function for an echo indicator, and then the first and second echoes are filtered out with finding peaks. Offset time is compensated by the zero-crossing method. Thickness can be computed on a point of the zero-crossing method. A statistical test was performed to evaluate data reliability obtained from ultrasonic thickness measurements; moreover, the method is compared to the highest reliability and accuracy method based on computation as a cross-correlation function [4].

2. Proposed method

Figure 1(a) presents a recorded waveform of echoes reflected from the interfaces of multiple layers including a direct wave, liquid-solid interface, and solid-solid interface. The thickness of specimens was focused only on the A and B echoes because the A echo was the top surface (liquid-solid interface), the B echo was the bottom surface (solid-liquid interface) reflected from the specimen. One problem is that there are many peaks on an interesting point. Based on the procedure developed with the help of an analytical function, the recorded signal is carried out on the Hilbert transform that produces a function of a real variable given by convolution with the function $1/\pi t$. The basic Discrete Hilbert Transform (DHT) of a received signal [5]. The analytic signal obtained from the Hilbert transform is shown in Fig. 1(b). Areas in which echoes are reflected from the top and bottom interfaces of specimens are positioned at the second and third peaks. The time difference between these peaks defines the traveling time for a sound wave to move through a specimen with a constant velocity. TOF$_1$ and TOF$_2$ are arrival time of top and bottom surface, respectively.

Next, the selected signals must be extracted from the unwanted signal. Figure 2(a) shows the signal length of both echoes. Maximum value of each echo in Fig. 1(b) corresponds to the number 2 in Fig. 2(a). TOF is focused on number 1 because the actual traveling time is from the start point of number 1. This is a point which is misunderstood in the conventional cross-correlation. A sample at the peak value ($T_p$) of the number 2 is then counted down until it meets with a third zero-crossing point as shown in Fig. 2(b). The other peaks except for the second and third are filtered out. TOF can be computed as follows:

$$TOF = T_p - \Delta t_1 - \Delta t_2 - \Delta t_3 \quad (1)$$

The thickness ($D$) of the carbon steel is computed as

$$D = \frac{\text{v}_{\text{sound}} \cdot (\text{TOF}_2 - \text{TOF}_1)}{2}, \quad (2)$$

$v_{\text{sound}}$ is sound velocity in carbon steel. Every point on the
specimen had a reference value obtained using a precise measurement system and inspectors measured the thickness for all these points.

3. Experimental results

In Fig. 3, the thickness of thin-walled carbon steel plate was evaluated by ultrasonic thickness measurement following an experimental setup made up of a pulse transmitter/receiver (pulser/receiver), a waterproof ultrasonic transducer, data acquisition, a computer, a water container and specimens. A commercial transducer was used to transmit and receive longitudinal echo mode. The USB NI 5133 operated at a sampling rate of 100 MS/s. Signal express 2015 was performed for recording data and saving into a destination file. The proposed method was implemented on the open access Python 2.7 program. An ultrasonic wave was transmitted from the pulser/receiver and echoes reflecting from the top and bottom surfaces were detected by an ultrasonic probe suitable for 4 MHz. Plate thickness was setup at several sizes. Propagation velocity of a sound wave in carbon steel is approximately 4,880 m/s at 22°C. Specimens used for testing had thickness at 2, 3, 5, and 7 mm; each specimen had ten inspection positions according to the A-scan method. Distance between the ultrasonic probe and specimen was located at 3 cm from the surface.

A series of known carbon steel thickness were prepared and the proposed method was evaluated. Figure 4 shows the error of each marked point on the A-scan of the specimen. The HTZC algorithm was used to measure accuracy which was identified at approximately 50 μm for thickness of 3, 5, 7 mm. At the 2 mm thickness there were overlapped echoes during the zero-crossing point of the second and third echoes which resulted in deviation of the measurements. Figure 5(a) shows the probability density function (PDF) of the measurements.
on each position of specimens. All points were sampled with 200 pieces of data. Figure 5(b) is the variance measurements for each thickness. For thickness of 3, 5, 7 mm, most samples were positioned close to the average value which guaranteed high precision of the proposed HTZC method. Thickness at 2 mm had the highest variance compared with the others. Variance was computed using root mean square error (RMSE). Cumulative density function of 2 mm showed a relatively larger variance because samples of 2 mm varied from 0% up to 100% wider than the others. At 3 mm, samples could change from 0% up to 100% with RMSE at 0.084 mm. Lowest variance was found at 7 mm thickness with RMSE at 0.053 mm. Measurement quality recorded comparatively lower variance when the carbon steel became thicker because thickness positively correlated with space of specimens. When thickness was over 2 mm, the probability of overlap between the second and third echoes decreased. Seven millimeters of carbon steel provided the smallest uncertainty. To test efficiency against other techniques, the most reliable and accurate ideas relied on computation of a cross-correlation function between reflections from the interface. The peak of reflected echoes from the cross-correlation technique was not so clear as that from the Hilbert transform. Figure 6 presents a comparison of measurement accuracy of average values of the carbon steels. The proposed HTZC method had higher accuracy than the cross-correlation technique at around 0.1 mm as shown in Fig. 6(a). Comparison of variance is shown in Fig. 6(b). The HTZC had smaller deviation than the cross-correlation technique.

4. Conclusion

For ultrasonic measurement of thin-walled hot-rolled structural carbon steel, ultrasonic echoes reflected from the target can overlap with direct ultrasonic waves generated from the probe. This wave overlapping made the thickness impossible to measure since the ultrasonic technique requires an isolated echo reflected from the layers. Here, we used an immersion technique to separate direct sound and reflected echo. Thickness measurement was determined by a pulser/receiver, a high standard ultrasonic probe, and a digitizer. We proposed a fast signal-processing method, called HTZC, to obtain accurate results. The algorithm was implemented on Python 2.7. In the experiments, accuracy and precision were evaluated with PDF and CDF. Repeatability was determined via 200 measurements at each thickness. Results showed a good agreement with a series of known thickness from 2 mm up to 7 mm. For 2 mm thickness, there was overlapping between the second and third reflected echoes. This led to miscalculation and decreased accuracy. Results indicated that this proposed method can measure thin-walled thickness of hot-rolled structural carbon steels robustly and provide higher accuracy than the cross-correlation method.

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References