Ultrasound Thickness Estimation using Cross-Correlation and Phase-Shift

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Abstract — In this paper the cross-correlation and phase-shift techniques are used for material thickness estimation. The cross-correlation is used to measure the time a transmitted signal takes to arrive at the receiver or the time between two successive received signals (multiple echoes). Whereas the phase-shift technique measures the time delay (less than a sine wave period) between transmitted and received sine waves. Combination of the correlation and the phase-shift techniques is also employed in this paper. The thickness is then estimated from the measured times and the ultrasonic waves speed in the material under test.

I. INTRODUCTION

Material thickness estimation is very important in quality control (e.g. tanks, layer, and sheet thicknesses) and in corrosion monitoring [1][2]. Ultrasonic waves can propagate in most materials used in industry, for example: metals, plastics, glasses, and ceramics. With these waves one can perform quick and reliable measurements, achieve high resolution, and measure in cases where mechanical methods are impractical due to object size and accessibility.

In a through-transmission setup [3], as shown in Fig. 1, the thickness d of a material can be estimated by measuring the time a transmitted signal takes to arrive at the receiver. This time is called the time-of-flight (TOF). Knowing the speed of ultrasound c for the material under test we can determine its thickness by:

\[ d = c \cdot \text{TOF} \]  \hspace{1cm} (1)

For applications where only one side of the object under test is accessible, a single transducer working as both, transmitter and receiver, can be used. The limitation of using a single transducer is that it implies a minimum measurable distance, as one has to wait for the end of transmission before reception. Another disadvantage is that with a single transducer, the transmitted signal has to propagate twice the time when compared with the two transducers setup. Thus, the received signal’s amplitude will be lower, leading to a lower signal-to-noise ratio (SNR).

In contact ultrasonic testing [3], a coupling medium between the transducers and the material under test, shown in Fig. 1, is typically used. It is necessary because the acoustic impedances of the active element material (e.g. piezoelectric) and the material under test are not matched, leading to high reflection at the interfaces. Thus, the coupling medium is used to improve the matching between these acoustic impedances, increasing the transmission coefficient.

One of the most common digital signal processing techniques for TOF measurement is the threshold technique [4]. It operates by detecting the first time the received signal crosses a previously set threshold. This operation is shown in Fig. 2. One of the limitations of the threshold technique is that it estimates a time-of-flight (TOFe) that is larger than the true one (TOFtrue). This happens because the threshold must be set higher than the noise level and also due to the received signal relatively long rise time. The narrow bandwidth of the system causes this rise time. Another difficulty in this method is to dynamically set the threshold level. Nevertheless, this technique is simple, fast, and can be used when high accuracies are not required.

In this paper we use cross-correlation and phase-shift techniques for TOF measurement in order to achieve high resolution thickness estimation. The structure of the paper is as follows: Section II briefly describes the cross-correlation and phase-shift techniques, shows how to use them for time-of-flight measurement, and also presents the main uncertainty sources encountered in this task. Section III describes the experimental setup. The experimental results and a

![Fig. 1. Through-transmission setup for thickness estimation.](image)

![Fig. 2. Threshold technique for time-of-flight measurement in a 5 mm steel (c = 5920 m/s) test block.](image)
discussion about them are given in Section IV. Finally, Section V presents the main conclusions from this work.

II. TIME-OF-FLIGHT MEASUREMENT

A. Cross-Correlation Technique

The cross-correlation is performed to determine the time at which two signals are most similar. Mathematically, the discrete-time cross-correlation between two signals $f[n]$ and $g[n]$ of length $N$ is represented as:

$$\varphi_f[r] = \sum_{n=0}^{N-1} f[n]g[n+r], \quad 0 \leq r \leq N-1$$

(2)

Note that $f[n] = f(nT_s)$, where $T_s$ is the sampling period. Thus, we want to find the time $r$ that maximizes $\varphi_f$. This situation will occur when the transmitted signal reaches the receiver. We perform the cross-correlation in the frequency domain to benefit from the Fast Fourier Transform (FFT) efficiency. Basically, we determine the FFT of both transmitted and received signals, multiply their spectrums, and then perform the inverse of FFT to obtain the time-domain correlation signal.

B. Pulsed Measurement Modes

We use the cross-correlation technique to measure the time-of-flight in two ways: 1) Mode A: measure the time between the transmitted signal and the first received signal, and 2) Mode B: measure the time between the first received signal and the first backwall echo, divided by 2. These two modes are shown in Fig. 3.

The TOF estimated in Mode A includes delays due to the coupling medium and pressure between the transducers and the material under test, the received signal relatively long rise time, and other system delays. The rise time of the received signal is due to the narrow bandwidth of the ultrasonic transducers. This causes a large error on the correlation result. Thus, calibration should be performed. Typically, a test block of known thickness and speed of ultrasound is used for this purpose [1][2]. However, this speed is commonly stated with a tolerance, leading to uncertainty in the estimated thicknesses. Hence, calibration is extremely important in high accuracy ultrasonic thickness estimation.

Note that for each thickness to be estimated the coupling layer and applied pressure are different. Therefore, some errors are virtually impossible to be corrected by this calibration procedure (test block).

As mentioned before, the TOF estimated in Mode B results from the time difference between the first and the second received signals. The same delay (due to correlation, coupling medium and pressure) is present in each time measured. Thus, the final TOF, in Mode B, does not include this delay, leading to higher resolution TOF measurement.

C. Phase-Shift Technique

In this technique a sine wave is transmitted and the phase-shift $\Delta \theta$ between it and the received sine wave is measured. The thickness estimated from the phase-shift $d_{ps}$ is given by:

$$d_{ps} = \frac{(\Delta \theta) \lambda}{360}$$

(3)

Where $\Delta \theta$ is the phase-shift (PS) in degrees and $\lambda$ is the wavelength. Note that this technique only permits thickness measurements up to a wavelength. That is, for longer distances phase ambiguity occurs, as can be seen in Fig. 4. In this example, we have four thicknesses ($3 \lambda + \Delta d$, $2 \lambda + \Delta d$, $\lambda + \Delta d$) that would cause the same measured phase-shift $\Delta \theta$.

Therefore, to be able to use this technique for estimating thicknesses longer than a wavelength, we need to know the integer number of wavelengths $n$ that are within the thickness to be estimated [5]. We use the TOF estimated from Mode A to determine $n$ and then use the thickness estimated from the phase-shift $d_{ps}$ (Mode A+PS). A sine-fitting algorithm [6] is used to estimate this phase-shift.

Fig. 3. Transmitted and received signals, and their cross-correlation in a 25 mm steel material ($c = 5920$ m/s).

Fig. 4. Ambiguity problem associated with the phase-shift technique.
The final thickness estimation \( d_{\text{final}} \), with this combination, is given by:

\[
d_{\text{final}} = n\lambda + d_{ps}
\]  

(4)

The error in the TOF estimated in Mode A must be less or equal to half of the sine wave period to perform this combination [5]. A larger error would lead to an error of, at least, one wavelength in the final thickness estimation \( d_{\text{final}} \).

As in Mode A, the coupling pressure here is also a source of uncertainty. Furthermore, the fact that here we are dealing with a continuous wave (CW) mode technique, the multiple echoes interfere with each other, causing measurement errors [7]. In an attempt to avoid this problem we measure the phase-shift between the first few periods (before interference) of the transmitted and received sine waves, as the time taken for the first backwall echo to arrive at the receiver is three times larger than the time taken by the first received signal.

D. Principal Uncertainty Sources in Thickness Estimation

Observing equation (1) it’s easily seen that the uncertainty in thickness measurements [1][2][7] can only come from uncertainties in the speed of ultrasound in the material under test and/or in the measured time-of-flight. Note that in the phase-shift method we are actually also measuring the TOF, but because it does not use pulses, it is uncommon to refer to this method as a TOF based method. The uncertainties in the speed of ultrasound can be caused by temperature fluctuations and by material anisotropy. On the other hand, the TOF measurement is influenced by:

- Sampling rate of the analogue-to-digital converter (ADC);
- Coupling layer and pressure (Mode A and A+PS only). The speed of ultrasound in the coupling medium is typically smaller than the one in the material under test. This introduces some error, as we only use the speed in the material under test when determining the thickness;
- Surface roughness. If the surface is not smooth, the coupling between the transducer and the material under test is influenced;
- Digital signal processing Technique employed (e.g. threshold, correlation, phase-shift);
- Wave attenuation in the material. The higher the attenuation the lower the SNR, which in turn increases the uncertainty in TOF measurement;
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As we can see there are many sources of uncertainty in thickness estimation. Thus, if high resolution is to be achieved, care about these factors should be taken.

III. EXPERIMENTAL SETUP

The experimental setup that we have used to validate the presented techniques is shown in Fig. 5. It consists on the ATG T2, a commercially available steel step calibrator, available from Advanced Technology Group [8]. The thickness measurements were performed at the 5, 10, 20, and 25 mm steps. The specified tolerance is ± 20 µm.

The ultrasonic transducers that we have used, shown in Fig. 6, are the MRD-2501-HR model from Technisonic [9]. They have the following characteristics: 25 MHz nominal resonant frequency and 3.175 mm active element diameter. The coupling medium used between the transducers and the surfaces of the material under test is the UCA-6 from Ely Chemical [10].

The signals were generated by an Agilent 33250A function generator and the data acquisition was performed by a Tektronix TDS 3052 digital oscilloscope.

We have developed a graphical user interface (GUI) in Matlab. It permits an easier and quicker way of using the various implemented functions. Fig. 7 shows its front panel. The GUI permits the loading of the measured signals, the selection of the measurement technique (Mode A, Mode B, and Mode A+PS) to be used. The ultrasound speed for the material under test must be entered. It displays the measured time-of-flight and the correspondent thickness.

IV. EXPERIMENTAL RESULTS

We have performed the following thickness estimation experiments: Mode A, Mode B, and a combination of Mode A and the phase-shift technique (Mode A+PS). A calibration was previously performed against a commercially available steel test block (ATG K1) from Advanced Technology Group, which has the same ultrasound speed as the material under test (ATG T2 step calibrator). The manufacturer states 5920 ± 30 m/s for the speed of ultrasound.
In Mode A, Mode B, and in the first step (integer number of wavelengths estimation) of the combination method, we have transmitted a burst of 5 sine wave periods at the actual transducer resonant frequency (22.2 MHz). In the phase-shift step we continuously transmitted a sine wave at this frequency. The results obtained are shown in Table I. The values of $E_{A}$, $E_{B}$, and $E_{APS}$ are the errors in each mode when the speed is 5920 m/s. The ±30 m/s speed uncertainty leads to uncertainty in the estimated thickness, represented by ±$E_{A}$, ±$E_{B}$, and ±$E_{APS}$, respectively. Results shown in Table I are also plotted in Fig. 8. The uncertainty in the estimated thicknesses error is represented by the bars. We intentionally made the bars not coincident with a given nominal thickness for better visualization.

One should not forget that the thicknesses estimated in Mode B don’t include the coupling effect as in the case of Mode A and Mode A+PS, leading to higher thickness estimation accuracy.

We can see in Fig. 8 that the errors associated with Mode B are within the manufacturer’s specified tolerance (± 20 µm) and that its uncertainty increases with the nominal thickness value (lower SNR). An uncertainty of one wavelength can occur in the error of the combined method, when the Mode A error uncertainty is large, leading to uncertainty in the integer number of wavelengths estimation. When this is not the case, the uncertainty of the Mode A+ PS is lower than the Mode A alone.

The fluctuations (Mode A and A+PS) in the estimated thicknesses error can be explained by the different coupling pressures at each calibrator step. Besides all these uncertainties, the error for most of the presented nominal thicknesses is lower than a wavelength ($\lambda = 266.67 \pm 1.35$ µm).

V. CONCLUSIONS

We have presented three methods for ultrasonic thickness estimation. The measurement principle was the TOF measurement, using the cross-correlation technique alone or a combination of it with the phase-shift technique. The TOF measurement based on the first received signal (Mode A and A+PS) permits the measurement of large thicknesses. However, the errors associated with the correlation technique and with coupling are not completely compensated, due to differences in the calibration block and the material under test (ultrasound speed) and also due to the different coupling pressures in the calibration and in the actual measurement stages. Thus, pressure uniformity should be maintained for repeatable measurements. On the other hand, the TOF measurement based on first received signal and the first echo (Mode B) is limited to shorter thicknesses due to the attenuation in the material under test. Nevertheless, this method virtually removes the errors associated with the correlation procedure and coupling. The combination of Mode A and the Phase-shift method reduces error of thickness estimation by Mode A alone, as long as the TOF estimated by Mode A is accurate enough.

**REFERENCES**


