

Monitoring of Pipe-Wall Thickness and its Thinning Rate by Ultrasonic Technique

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Abstract: An important issue in power generation and petrochemical industries is the monitoring of pipe wall thickness and corrosion/erosion rate. The pipes are usually subject to erosive and/or corrosive environments and any failure could be catastrophic. While periodic manual ultrasonic thickness measurement is the common practice in many industries, in certain cases, where higher accuracies are required, continuous monitoring systems are required. This paper introduces a measurement algorithm that can accurately measure the pipe wall thickness and estimate the pipe-wall thinning rate. The algorithm incorporates a model-based estimation technique for estimating the pipe wall thickness and thinning rate. It is an on-line non-intrusive ultrasonic thickness measurement tool for quick and accurate estimation of the erosion/corrosion rate and remaining pipe-wall thickness. The technique is applied to data measured from a pipe carrying high temperature liquid. The results show that the system can measure thinning rates as low as 10 $\mu\text{m}/\text{year}$ within 5 days of data collection.

Keywords: Corrosion, Model-Based Estimation, Nondestructive Evaluation, Ultrasonic

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1 INTRODUCTION

Ultrasonic thickness gauging, eddy current, and magnetic flux leakage are conventional nondestructive testing (NDT) techniques widely used for offline evaluation of pipe wall thickness during periodic maintenance shutdowns, typically once every one to two years. There are also intrusive methods used for monitoring pipeline corrosion, whereby a sensing device is inserted into the pipe and is subjected to the corroding environment. Such techniques used a variety of probe types including: coupons, electrical resistance, linear polarization, and galvanic probes for which the data collection is performed offline and the process is labor intensive [1].

These techniques result in an estimate of the average material removal rate over a long time period, but yield no information on short-term process-related perturbation of the thinning rate. This shortcoming has highlighted the need for a greater emphasis on on-line monitoring of corrosion/erosion as a continuous process. This may enable optimization of a plant's processes to bring the erosion or corrosion problem under control before damage becomes extreme. The most common non-intrusive technique is based on on-line ultrasonic thickness measurement.

In this paper, implementation and optimization of this technique are investigated. The objective is to develop an online, non-intrusive ultrasonic system for quick and accurate estimation of the pipe wall thinning rate. In power generating industry, moisture separator reheater (MSR) drains, heater subject to high flow accelerated corrosion. At the moment, corrosion inhibitors are deposited on the inside surfaces of pipes in order to reduce their thinning rate.

To evaluate promptly the success of such corrosion inhibition measures, one needs to determine the thinning rate before and after this type of surface treatment. Conversely, it is also important to immediately assess the potential for erosion/corrosion damage to a plant's piping system following an unintended event that releases a corrosive agent or particulates into a system.

In this paper, pipe wall thickness is measured, using a model-based estimation (MBE) technique. The developed method is applied to experimental data obtained from an accelerated corrosion test apparatus. The thinning rate of the pipe wall is also measured as a complementary result. The MBE technique is compared against the cross-correlation technique previously developed for this purpose by the authors [2].

2 BACKGROUND

The working principle of a typical ultrasonic thickness gage is shown in Fig. 1. An ultrasonic pulse propagates through a delay line and is transmitted into the pipe wall where it reverberates, generating a series of regularly spaced reflections (backwall echoes). The reflected waveform is then detected by the same piezoelectric element. The wall thickness is equal to half the echo intervals (in μs) multiplied by the sound velocity.

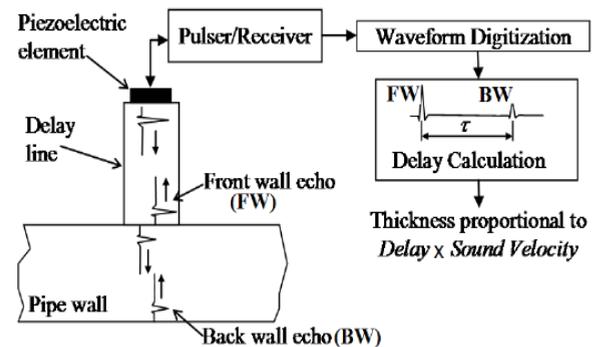


Fig. 1 Working principle of a typical ultrasonic thickness gauge

The primary source of error in estimating pipe wall thickness is the measurement of delay time between the front wall (FW) and backwall (BW) echoes. The thinning rate over a time period Δt is:

$$\text{rate} = (\Delta\tau \times c_L) / 2\Delta t \quad (1)$$

where $\Delta\tau$ is the round trip travel time of the wave in pipe wall and c_L is the speed of longitudinal waves in the pipe material. In this study, the following key assumptions are made regarding the ultrasonic echo signal received by a transducer permanently mounted on the outer wall of the pipe:

1. All random electrical noise in echoes received by a transducer can be removed through signal averaging.
2. The total system response function can be approximated by a superposition of a low-amplitude deterministic background noise (grain boundary reflections, stray pulses in the transducer coupling layer, etc.) with a series of equally spaced larger echoes, originating from the delay line and backwall reflections.
3. The deterministic background noise is invariant; only the large backwall echoes move slowly to the left along the time axis as the material corrodes/erodes. This assumption is based on the premise that a transducer's performance will not change in any given time period

in which the thinning rate is to be measured (typically a few days).

3 THEORY

3.1 Model-Based Estimation (MBE) Technique

A linear ultrasonic system's output can be expressed as a convolution of the transfer function $x(t)$ of the test piece (a discrete sum of sharp spikes), and the material and electronic system's impulse response $h(t)$ [3]:

$$y(t) = x(t) * h(t) + e(t) \quad (2)$$

The term $e(t)$ represents the random additive noise assumed to vanish by temporal averaging; it is not to be considered any further in this study. For the case of thickness measurement, the test piece transfer function $x(t)$ would ideally consist of a sequence of spikes that are equally spaced in time. The total echo signal is distorted by the response of the correlated noise, $x_b(t)$, originating from grain boundaries, reflections within the transducer and coupling layer, and electronics such that $y(t)$ is now given by:

$$y(t) = [x(t) + x_b(t)] * h(t) \quad (3)$$

The shape of the wavelet $h(t)$ is typically estimated from a low-noise flat reflector such as the backwall of a very smooth plate. However, for the purpose of online thinning rate measurements, the transducer cannot be periodically removed from the pipe for this purpose. In high temperature applications, transducer aging over time and changing plant operating conditions render the upfront collection of a reference echo ineffective. As a result, the precise profile of $h(t)$ is unknown in our case.

In the MBE algorithm, a Gaussian profile is used for modeling each ultrasonic echo. A Gaussian pulse is expressed as a function of five parameters $\theta = (\alpha, \tau, f_c, \varphi, \beta)$, as follows [4]:

$$x'(\theta, t) = \beta e^{-\alpha(t-\tau)^2} \cos[2\pi f_c(t-\tau) + \varphi] \quad (4)$$

where α is the bandwidth factor in MHz^2 , τ is arrival time, f_c is center frequency in MHz, ' φ ' is phase in radians, and ' β ' is amplitude. The three parameters (α, f_c, φ) define the shape of the reference wavelet and hence are shared among all echoes received from a test specimen (assuming negligible dispersion). The other two parameters ' β ' and τ represent the amplitude and time of arrival of each echo, which are different for the

various echoes. $x'(t)$ can be considered as the convolution of one discrete spike of $x(t)$ with $h(t)$.

Our objective is to use pulse-echo measurements acquired over a specified number of days to estimate the average erosion/corrosion rate over that time period, such as 5 or 15 days. Each FW and BW echo of every waveform is slightly distorted by the background noise in a slightly different manner. We can therefore use all of the waveforms collected over the measurement period to find a single set of best values of ' α ', ' f_c ' and ' φ ' via an optimization algorithm. (Experience shows that if a subset of these waveforms is used, e.g. every fifth waveform, comparable results are achieved). In the next step, the two remaining parameters ' β ' and τ are optimized for the FW and BW echoes.

Several variations of the MBE algorithm were assessed. The MBE algorithm that showed good stability in minimization of the difference between the experimentally collected waveform $y(t)$ and their respective modeled Gaussian pulses was a non-linear least square scheme:

$$\sum_P \min \|y(t) - [x'_1 + x'_2]\|^2 \quad (5)$$

where ' x'_1 ' and ' x'_2 ' are the FW and BW echoes. In thickness measurement, P will be number of replicate of testing and in corrosion rate measurement, which is an online test; ' P ' is the number of waveforms in the selected time travel.

The Levenberg-Marquardt (LM) method is used to solve non-linear least squares objective function Eq. (6). The LM method acts more like a gradient-descent method when the parameters are far from their optimal value, and act more like the Gauss-Newton method when the parameters are close to their optimal value [5].

Fig. 2a shows the Gaussian pulse fitted to a FW echo and its corresponding frequency spectrum compared to that of the measured echo in Fig. 2b. Also, Fig. 2c shows the Gaussian pulse fitted to a BW echo and its corresponding frequency spectrum compared to that of the measured echo in Fig. 2d. In the time domain, the Gaussian pulse fits the measured echo well, with some deviation apparent at the trailing edge. The time-delay between the FW and BW pulses is found by differentiating the model curve in the neighborhood of each echo, and to find the location of its maximum/minimum value. These values are then corrected based on phase values of each Gaussian pulse.

After the second optimization is performed for a waveform, accurate Time of Flight (TOF) of the echo is estimated by setting the derivative of its Gaussian

model (with respect to t) equal to zero. Finally, time delay is the difference of TOF of each model at the same phase.

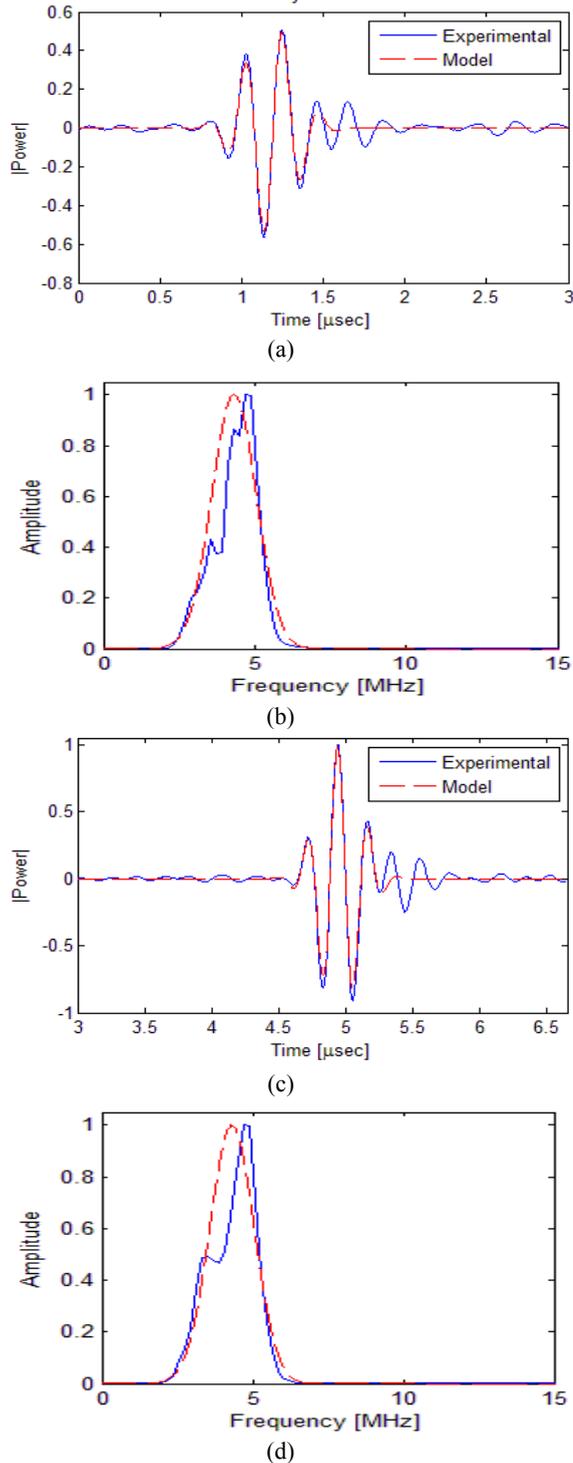


Fig. 2 a) A typical FW echo and its corresponding fitted Gaussian pulse, b) frequency spectra of the two echoes, c) A typical BW echo and its corresponding fitted Gaussian pulse, and d) frequency spectra

3.2 Temperature Compensation

The temperature affects corrosion rate are measured in two ways: 1) by changing the thickness of the specimen due to thermal expansion or contraction, and 2) by changing of the ultrasonic wave velocity. The thermal expansion of materials due to temperature variation is governed by linear thermal expansion coefficient.

$$d = d_0[1 + \alpha(T - T_0)] \quad (6)$$

where ' d ' and ' d_0 ' are the current and reference (at temperature ' T_0 ') thicknesses, respectively, and ' α ' is the thermal expansion coefficient of the material. The longitudinal wave velocity can be written in terms of the Young's modulus, ' E ', and Poisson ratio, ' ν ', as follows:

$$c_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (7)$$

According to [5], the equation governing the dependence of ' c_L ' on temperature is:

$$c_L(T) = \sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)} \frac{[E_0 + \beta(T-T_0)]^2 [1 + \alpha(T-T_0)]^2}{\rho}} \quad (8)$$

where ' E_0 ' is Young's modulus at reference temperature ' T_0 '. The coefficient ' β ' which governs the temperature dependence of E is defined as follows:

$$\beta = \frac{E - E_0}{T - T_0} \quad (9)$$

Although Eq. (9) is nonlinear in ' T ', Rommetveit et al., [6] showed that for carbon steel, at temperatures below 100°C, the relationship between velocity and temperature is nearly linear. This is consistent with the earlier results reported by Mak and Gauthier [7]. In this paper, the parameters of Table 1 have been used to describe the steel piping.

Table 1 Parameter values for carbon steel piping used in calculations [6]

Variable	E_0	ρ	ν	B	α	T_0
Value	210 GPa	7872 kg/m ³	0.295	-47.7 MPa/K	12.8 ppm/K	25 °C

4 EXPERIMENTS

The test system incorporates an Electro-Chemical Machining (ECM) principle to remove material from a delineated area on the inside surface of a section of a pipe [2]. It was designed to produce a year-long equivalent material removal of up to 3 μm per minute at maximum current. This implies a time acceleration factor of approximately 104 compared to the maximum erosion rate of 150 μm/year found in CANDU nuclear reactor feeder tubes. A 4 MHz high temperature piezoelectric transducer was mounted on the outside surface of the pipe using a soft foil shim as coupling agent, and a clamping mechanism pressed the transducer firmly against the shim and pipe wall.

Waveform data were collected during the accelerated corrosion test at a rate of approximately one waveform every 30 seconds. Each recorded waveform was the result of averaging 3000 measured waveforms; this effectively eliminated the effects of random electrical noise. Depending on the desired corrosion rate, the average current level was varied in steps between 0 mA and 109 mA. The experiment reported here took more than six hours and during this time, the average current setting (thinning rate) was adjusted to nine different levels, as shown in Fig. 3.

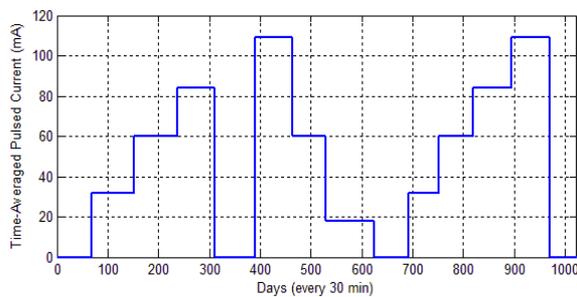


Fig. 3 Settings of average current levels during the accelerated corrosion experiment.

Using a deep throated micrometer, the thickness of the pipe wall was measured before and after the experiment.

5 RESULTS AND DISCUSSION

The experimental waveforms were processed by the MBE scheme and corrected for changes in pipe wall temperature. The time delays between the front wall and backwall echoes were found and the thinning rates were calculated during short time periods (several days). The thinning rate was assumed to be linear during these short time periods. Fig. 4 shows the variations of the pipe wall thickness estimated by the

MBE scheme during the experiment compared with the CC technique [8].

Using the MBE technique, the thinning rates were calculated using moving time periods of 5 days and plotted in Fig. 5a. The thinning rates were then estimated from the slope of the thickness data analyzed over the desired time period (5 days in Fig. 5a). Fig. 5a shows good correlation between thinning rate levels calculated from the ultrasonic data using the MBE algorithm, and the “measured” corrosion rate as inferred from the electric current time profile of the test system displayed in Fig. 3. Complementing Fig. 5a, the thinning curve obtained from the cross-correlation technique is shown in Fig. 5b [8].

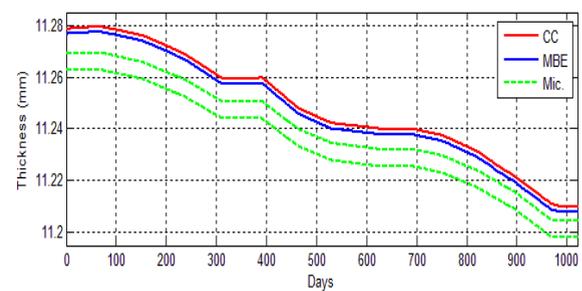
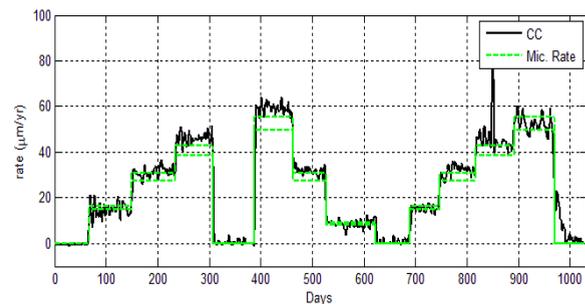
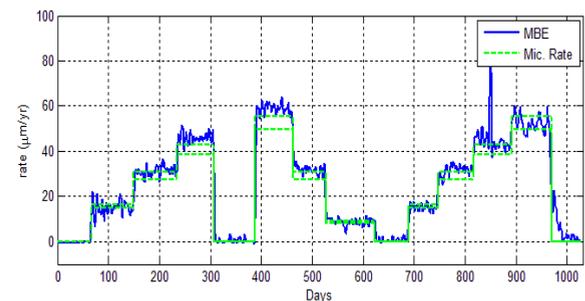


Fig. 4 Reduction of pipe wall thickness during the accelerated corrosion experiment



(a)



(b)

Fig. 5 Thinning rate estimated based on a moving sample of 5 days of data collection. The dotted lines show the 95% confidence interval of micrometer measurements

6 CONCLUSION

In this paper, a signal processing technique incorporating the MBE technique was used for measuring thickness and thinning rate of a pipe wall. Two echoes of the measured signal, one from the front wall and one from the backwall of the pipe were used for measuring thickness and thinning rate of the pipe. It was shown that the technique can detect thinning rates as low as 10 $\mu\text{m}/\text{year}$ in 5 days or less with a 95% confidence interval of $\pm 4 \mu\text{m}/\text{year}$. Comparison of the results with a cross-correlation technique [8], showed very good agreement between the two techniques. The MBE technique provides thickness results that are marginally more accurate than those of the cross-correlation algorithm. However, the MBE technique is more complex, less stable numerically and more expensive in terms of computation time. The technique is nonintrusive and can be used for online monitoring of the corrosion rate. Minimum operator involvement is required and rapid feedback can be provided for the effects of changes in coolant chemistry or other plant conditions.

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