HIGH RESOLUTION ULTRASOUND WALL THICKNESS MEASUREMENTS THROUGH POLYESTER COATING AND REAL-TIME PROCESS CONTROL

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ABSTRACT

Epoxy-, polyester-, paint and similar coatings are often used for external corrosion protection on pipelines and other process equipment. It is well known that ultrasound transducers can determine wall thickness through such coatings. This paper explores how the sensitivity of high resolution pulse-echo ultrasound measurements from permanently installed immersion sensors are affected by measuring through a 300 µm layer of polyester powder coating compared to measuring on plain steel. The results show that the standard deviation is below 6 nm for both specimens. Further, there is no degradation in the resolution when measuring through coating. Actually, the results show that measuring through the coating gives better resolution. This result is verified by examining the received acoustic energy from the two specimens by using a 1D signal model.

For many real-time corrosion monitoring applications it is important to estimate the corrosion rate as fast as possible. This paper also explores how one can incorporate the abovementioned ultrasound wall-thickness measurements into a recursive Kalman filter for optimal parameter estimation and process control. The results show that reliable corrosion rate estimates are obtained and that these correlate well with the measured temperature.

Keywords: Ultrasound, coating, temperature compensation, corrosion rate estimation, real time

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(1) Tarjei Rommetveit is on a leave from Sensorlink to pursue a PhD

INTRODUCTION

Employing ultrasound pulse-echo measurements is a well-established approach in the non destructive testing (NDT) community for measuring wall thickness and detecting defects[1]. When it comes to corrosion monitoring, ultrasound has some advantages compared to probe technology: First of all it is non-invasive, secondly it measures directly on the metal of interest and finally the ultrasound probes have no theoretical upper lifetime-limit. The drawback is that ultrasound techniques has been, and still is, considered too insensitive for many applications. However, advances in low-noise electronics, sensor technology and signal processing algorithms have made it possible to achieve sub-micrometer resolution using permanently installed ultrasound units[2, 3]. For an overview of corrosion monitoring techniques, see [4].

Most pipelines have an external corrosion protection coating. As ultrasound is a non-invasive method, one has to “see” through the coating when measuring on the metal. When sending an ultrasound pulse through such a layer, it will be distorted. The distortion depends on factors such as sound velocity, density, attenuation and thickness of the coating as well as ultrasound frequency. In order to be able to investigate the pulse distortion as a function of the coating and transmitted pulse, a signal model for plane waves in a layered medium is presented. This paper also explores how the sensitivity of high resolution ultrasound measurements from permanently installed sensors are affected by measuring through a 300 µm layer of polyester powder coating compared to measuring on plain steel.

Kalman filtering[5] is a recursive, model based algorithm for processing discrete, noisy measurements into estimates of the system’s state. If one can assume Gaussian noise, the Kalman filter gives the optimal estimate. The word “recursive” means in this respect that at each time-step, the new estimate is based on the previous estimate combined with the last measurement. Thus, one does not have to include all previous measurements in order to obtain the best estimate as is the case for standard least squares- and Wiener filtering techniques. This is an advantage for real-time applications. Kalman filters have a wide range of applications[6, 7]. The most well-known example of its use is in the GPS positioning system[8]. In this paper, a simple Kalman filter for optimal estimation of the corrosion rate based on temperature compensated wall thickness measurements is presented.

THEORY

This section discusses the signal model and theory related to temperature compensation, corrosion rate estimation and Kalman filtering.

Signal Model

A proper signal model is important in order to understand how the pulse changes while propagating through the coating. Often it is difficult to obtain the exact acoustic parameters of the coating, and a signal model may also be used for estimating such parameters. In this paper the signal model is used for investigating how the received acoustic energy depends on the coating.

In the following discussion plane p-waves are assumed. Even though focused transducers are used in the experimental setup, plane waves are a good approximation in the focal region for which we are most interested. Further, no surface roughness is integrated into the model. This is a good approximation when the roughness-dimensions are much less than a wavelength as is the case in this paper.

When measuring in pulse-echo mode on plain steel where the thickness is much larger than the spatial pulse spread, the received signal will be a reflected version of the incoming wave; besides amplitude reduction there are little changes in the pulse-form.

However, when measuring on a coated specimen, the received pulse-form will change if the coating thickness is smaller than the spatial pulse spread. Throughout this section, the pressure fields will be denoted as $p_{m\pm}(z) = P_{m\pm}e^{\mp jk_m z}$. Here $P_{m\pm}$ is the complex amplitude of the pressure wave. The subscript *m* indicate the material number and ± indicates the direction of propagation; '+' denotes propagation to the right while '-' denotes propagation to the left. Now consider the normal incident, harmonic plane wave $p_{0+}(z) = P_{0+}e^{-jk_0 z}$ propagating into a layered medium as shown in Figure 1. The structure illustrates a plate with thickness *L* (Material 1) next to a plate with thickness *h* (Material 2) immersed in material 0. The received signal P_{0-} is then a function of the reflected and transmitted waves in material 1 and 2. In our case material 0 is water, material 1 is the polyester coating while material 2 is the steel specimen. The sound speed and density in material *m* is given by c_m and ρ_m respectively. Note that Figure 4 shows examples of the recorded pulse-trains on plain steel and powder coated steel.

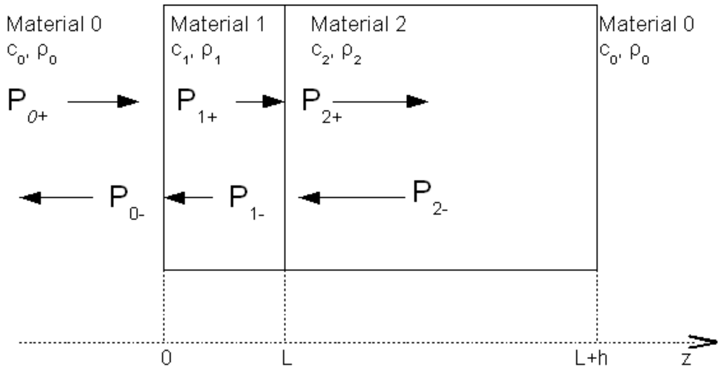

Figure 1 – Two layers with thicknesses *L* and *h* submersed in an infinite material 0. The incoming wave is P_{0+}, while the received echo is denoted by P_{0}-.

By following the discussion in [9, 10] and applying the principle of superposition one can develop the following relations between the complex envelopes:

$$
\begin{aligned}
F_+ &= \frac{P_{2+}}{P_{0+}} = \frac{T_{01}T_{12}e^{-jL(k_1-k_2)}}{1+R_{01}R_{12}e^{-2jk_1L}} \\
F_- &= \frac{P_{0-}}{P_{0+}} = \frac{R_{01}+R_{12}e^{-2jk_1L}}{1+R_{01}R_{12}e^{-2jk_1L}} \\
G_+ &= \frac{P_{2+}}{P_{2-}} = e^{2jk_2L}\left(\frac{R_{21}+R_{10}e^{-2jk_1L}}{1+R_{21}R_{10}e^{-2jk_1L}}\right) \\
G_- &= \frac{P_{0-}}{P_{2-}} = \frac{T_{21}T_{10}e^{-jL(k_1-k_2)}}{1+R_{21}R_{10}e^{-2jk_1L}} \\
E &= \frac{P_{2-}}{P_{2+}} = R_{20}e^{-j2k_2(h+L)}
\end{aligned}
\tag{1}
$$

In the above expressions, T_{mn} is the transmission coefficient from material *m* to material *n*, R_{mn} is the reflection coefficient from material *m* to material *n* and k_m is the possibly complex wave number in medium number *m*. These parameters are defined as:

$$T_{mn} = \frac{2Z_n}{Z_m + Z_n}$$
$$R_{mn} = \frac{Z_n - Z_m}{Z_m + Z_n} \quad (2)$$
$$k_m = \frac{\omega}{c_m}(1 - j\frac{1}{2Q_m})$$

where $Z_m = c_m\rho_m$ is the characteristic impedance of the medium, ω is the angular frequency, j is square root of -1 and Q_m is the mechanical Q-number. It's worth noting that the attenuation increases as Q decreases. An acoustic pulse will reverberate back and forth between the steel/coating- and the steel/water interface, generating multiple echoes. Letting ω be a variable, the transfer function relating the transmitted and total received pressure field can be expressed in the Fourier domain as

$$H(\omega) = F_-(\omega) + F_+(\omega)G_-(\omega)\sum_n E(\omega)^n G_+(\omega)^{n-1} \quad (3)$$

Here n is the number of echoes one wants to examine from the steel/water interface. The total received signal is a convolution between the transfer function and the incoming wave. Thus it can be modeled in the Fourier domain as

$$p_{0-}(w) = H(\omega)p_{0+}(w) \quad (4)$$

Here $p_{0+}(\omega)$ is the Fourier transform of the incoming pulse. By inverse Fourier transforming $p_{0-}(\omega)$, one finds the received pulse in time domain.

Temperature Variations

In 3 the temperature compensated wall thickness at temperature T is given by

$$d(T) = \sqrt{k(E_0 + \beta(T - T_0))\frac{(1 + \alpha(T - T_0))}{\rho_0}}\frac{tof}{2} \quad (5)$$

Here E_0 and ρ_0 are the Young's modulus and density at T_0 degrees Celsius, α is the linear thermal expansion coefficient, $k = \frac{1-\nu}{1-\nu-2\nu^2}$ where ν is the Poisson ratio, tof is the time of flight between 2 subsequent echoes and β is the linear thermal elastic modulus coefficient. The temperature dependence of E_0 is among others suggested in [11]. As this is a nearly linear function around T_0 one can approximate the function by a first order Taylor expansion:

$$d(T) \approx c_0\frac{tof}{2} + \frac{tof \cdot k}{4c_0\rho_0}(\beta + \alpha E_0)(T - T_0) \quad (6)$$

where $c_0 = \sqrt{\frac{kE_0}{\rho_0}}$.

Parameter Estimation Using a Discrete Kalman Filter

The corrosion rate is in general the time derivative of the wall-thickness. However, with noisy measurements it is not straight forward to differentiate the wall-thickness directly; one has to do some kind of estimation. In this paper, the approach is to use a 2 state Kalman filter.

The corrosion rate is assumed to be a Wiener process, i.e. following a random walk model. Thus we let the corrosion rate change with time. Between two subsequent measurements however, we assume the corrosion rate to be constant. In the continuous domain, we can thus model the state variables as

$$\begin{aligned} \dot{d}(t) &= a(t) \\ \dot{a}(t) &= u(t) \end{aligned} \tag{7}$$

where the dot denotes the derivative with respect to time, *u(t)* is white Gaussian noise, *d(t)* is the temperature compensated wall thickness given in Eq. (6) at time *t* and $a(t)$ is the corrosion rate. The state vector is now given in discrete time by

$$\mathbf{x}_k = \begin{bmatrix} d_k \\ a_k \end{bmatrix} \tag{8}$$

where the subscript *k* corresponds to the time at $t = k\Delta t$ where Δt is the interval between two successive measurements. The transition matrix *A* which relates the state at step *k -1* with the current state is given by

$$A = \begin{bmatrix} 1 & -\Delta t \\ 0 & 1 \end{bmatrix} \tag{9}$$

The measurement matrix *H* relating the temperature compensated wall thickness measurement $z_k = d_k$ to the current state is given by

$$H = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{10}$$

The measurement uncertainty *R* is assumed constant and it is calculated in advance by estimating the variance of the temperature compensated wall-thickness measurements

$$R = \sigma^2 = \frac{1}{N-1} \sum_{i=k}^{N} D(d_k)^2 \tag{11}$$

where *D(.)* is an operator which removes the linear slope. The process noise matrix Q is also assumed constant, and it is found by manual filter tuning. The complete operation of the Kalman filter algorithm is shown in Figure 2. Herein the matrix *B = 0*.

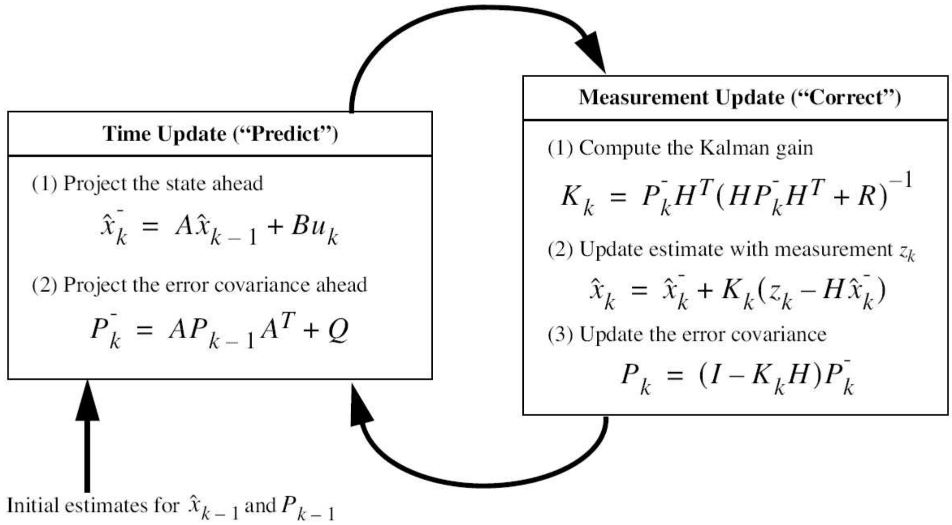

Figure 2 - Illustrating the operation of the Kalman filter. There is an ongoing cycle between predicting the next state of the process and updating the estimate by incorporating the last measurement.

EXPERIMENTAL SETUP

The experimental setup consists of two similar test cells filled with glycol immersed in a corrosive liquid. The test cells have end caps made of carbon steel. Glycol is used to avoid corrosion on the transducer-side of the specimens. One of the steel specimens is powder coated with 300 ± 5 µm beckrypol VJ-576-5087 from Dupoint. The coating thickness is verified with a coating thickness gauge. An immersion transducer from Imasonic is placed in each test cell separated with 15 mm standoff from the carbon steel. The glycol is then functioning as acoustic coupling medium between the transducer and the carbon steel. The active elements of the transducers are circular bowls made of piezo composite. The geometric focus of the transducer is 5 cm, and the diameter of the active element is 1 cm. As the test cells lie in corrosive liquid, the steel specimens will gradually corrode. The corrosiveness is modified by changing the pH. In order to reduce deposits on the specimen, a pump ensures circulation.
The temperature in the corrosive liquid is measured once for each wall-thickness measurement in order to perform temperature compensation. It is assumed that the specimens have the same temperature as measured.

All signals are recorded by an ultrasound hardware module developed by Sensorlink[12]. In order to reduce noise, the received signal is averaged 256 times in hardware before it is transmitted to a logging computer for further processing. The sampling frequency is 50 MHz.

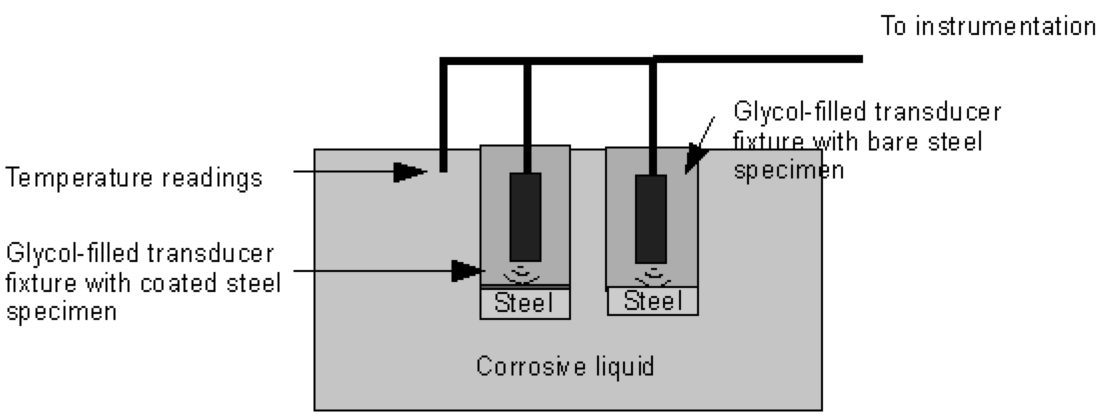

Figure 3 - Experimental setup for the corrosion experiment.

RESULTS AND DISCUSSION

Received waveforms and signal energy

Two back-wall echoes from the received waveforms are presented in Figure 4. Note that more acoustic energy is received from the coated steel. The received energy is proportional to the signal to noise ratio which again is a key parameter for the resolution of the wall-thickness measurements. As we will see in the next section, the resolution of the wall-thickness measurements from the coated specimen is better than for the bare steel. In this section the signal model will be used for verifying that one actually receives more energy from the coated specimen and that it is not an artifact coming from misalignment of the transducer, different transducer performance, etc.

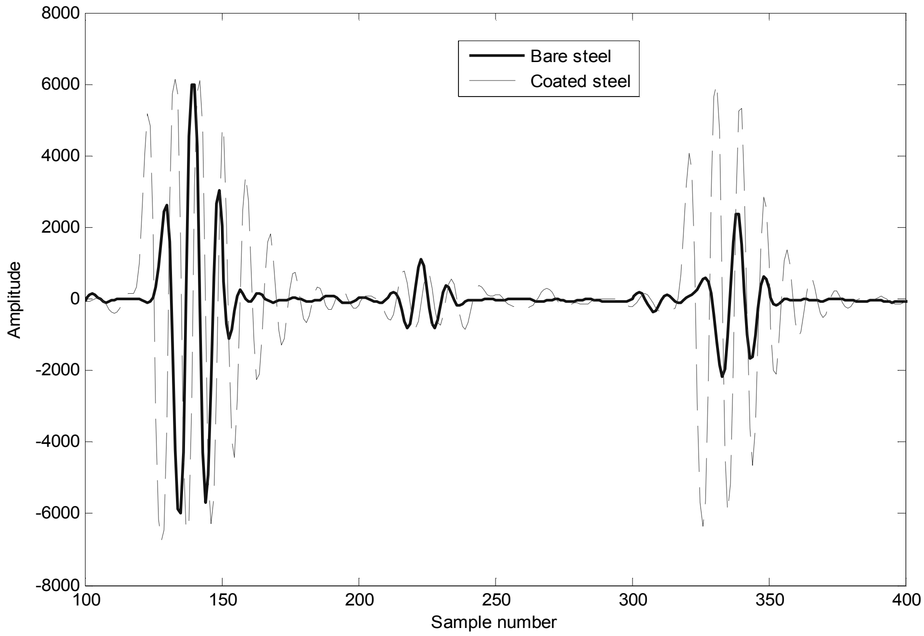

Figure 4 – Received waveforms when measuring on plain steel (solid line) and coated steel (dashed). The amplitude is given in arbitrary values.

A genetic algorithm inversion scheme is used for fitting the signal model given by Eqs. (3) and (4) to the received data from the coated specimen. See e.g. [13] for an introduction to inversion using genetic algorithms. The result of the fitting is shown in Figure 5 and Table 1. One can see from Figure 5 that the model captures many of the features as far as pure pressure waves are concerned. Since mode converted pulses (i.e. pulses which has partly propagated as share waves) are not integrated in the model, it is straightforward to distinguish them from the pure pressure waves when comparing with the measured waveform. The material data obtained from the fitting corresponds well to values found in the literature.

Table 1 – The optimized parameters are found from the genetic algorithm inversion scheme. The fixed parameters are obtained from measurements.

Optimized parameter	Value	Fixed parameter	Value
Sound speed, coating	2682 m/s	Sound speed, steel	5950
Thickness, steel	11.78 mm	Thickness, coating	300 μm
Q-number of steel	751	Impedance of water	1.5 MRayl
Q-number of coating	39.8	Impedance of steel	46 MRayl
Impedance of coating	3.0 MRayl		

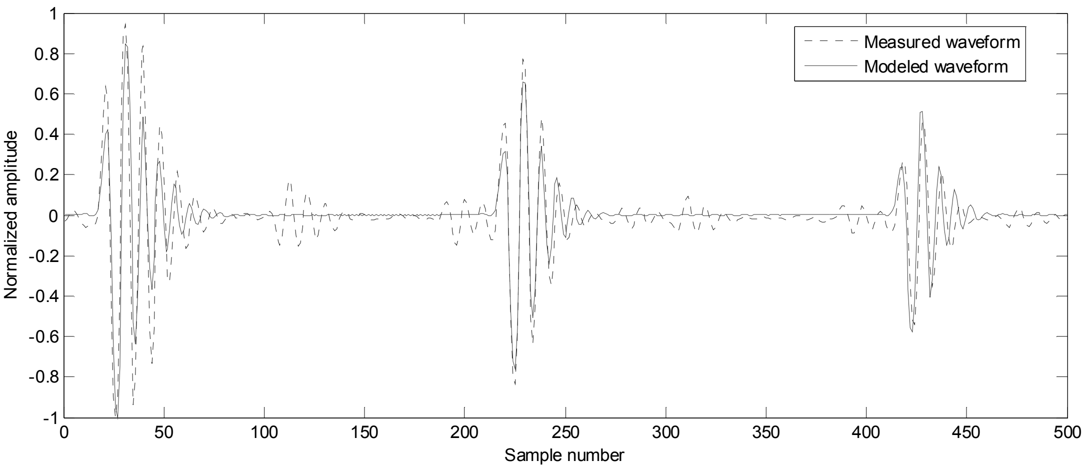

Figure 5 - Modeled and measured waveforms from the coated steel specimen. The amplitude is given in arbitrary values.

The received energy from the coated specimen will in general be a function of the attenuation and thickness of the coating as well as the pulse-form and -frequency. The frequency is related to the wavelength, λ, through the simple relation $f = c/\lambda$. The attenuation model given in Eq. (2) suggests the attenuation increases linearly with frequency. Put in another way; Eq. (2) implies that decreasing the wavelength or the Q-number will increase attenuation. Figure 6 presents how the received pulse amplitude from the back-wall varies with the ratio L/λ and the *Q*-number. Here *L* is the coating thickness. The Q-number for polyester- and epoxy coatings typically lies in the range 25-45.

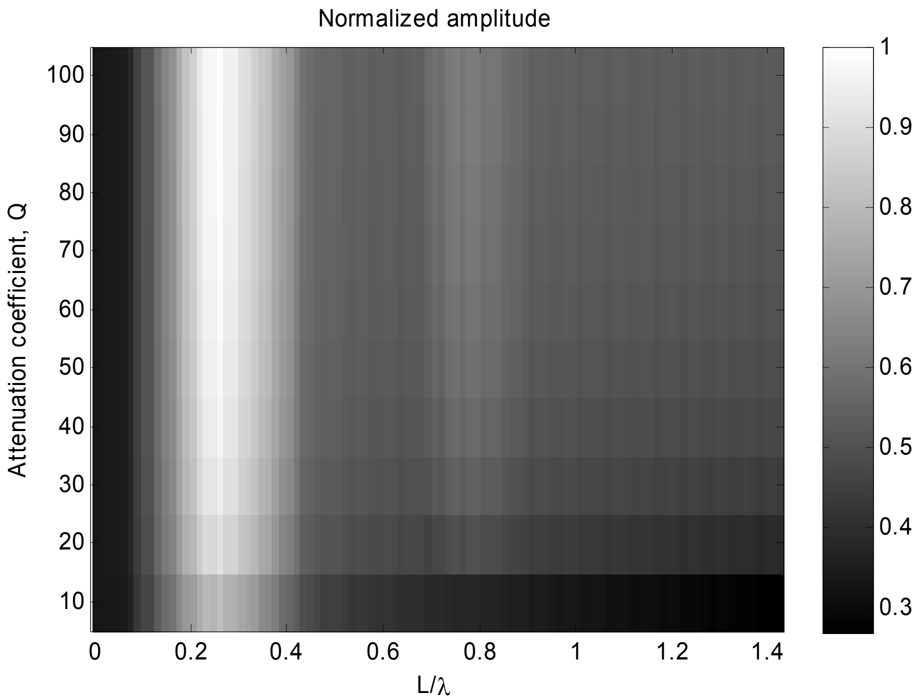

Figure 6 – Received amplitude from the back-wall as a function of the coating's Q-number and L/λ.

The amplitude received from plain steel is given for $L/\lambda = 0$ and this configuration only gives 34% of the maximum received signal amplitude. The maximum amplitude is received when $L/\lambda = 0.25$ which is due to the quarter wave resonance. In the experiment presented herein, the centre frequency is 5.3 MHz, c = 2682 m/s, Q = 39.8 and L = 300 μm which yields $L/\lambda = 0.59$ and a received amplitude of 50.3% of maximum. This is certainly more than for the plain steel. Based on Figure 6, it is only coatings thicker than 1 wavelength with Q ≤ 10 which gives a less signal amplitude than for bare steel for the back-wall echo.

Measured wall thickness and estimated corrosion rate

Figure 7 illustrates the measured wall-thickness on the bare steel- and powder coated steel specimen during a 3.5 month period respectively. When examining Figure 7 one can see that the temperature compensated wall-thickness appears much smoother than without compensation due to the removal of thermal noise. Also note that temperature peak around 1/6 seems to initiate corrosion on both specimens and that this is detected by the measurements quite rapidly. After 11/7 the corrosion stops according to the measurements on the coated specimen while it continues on the bare steel specimen. This may be due to local effects such as different flow conditions or rust deposits properties.

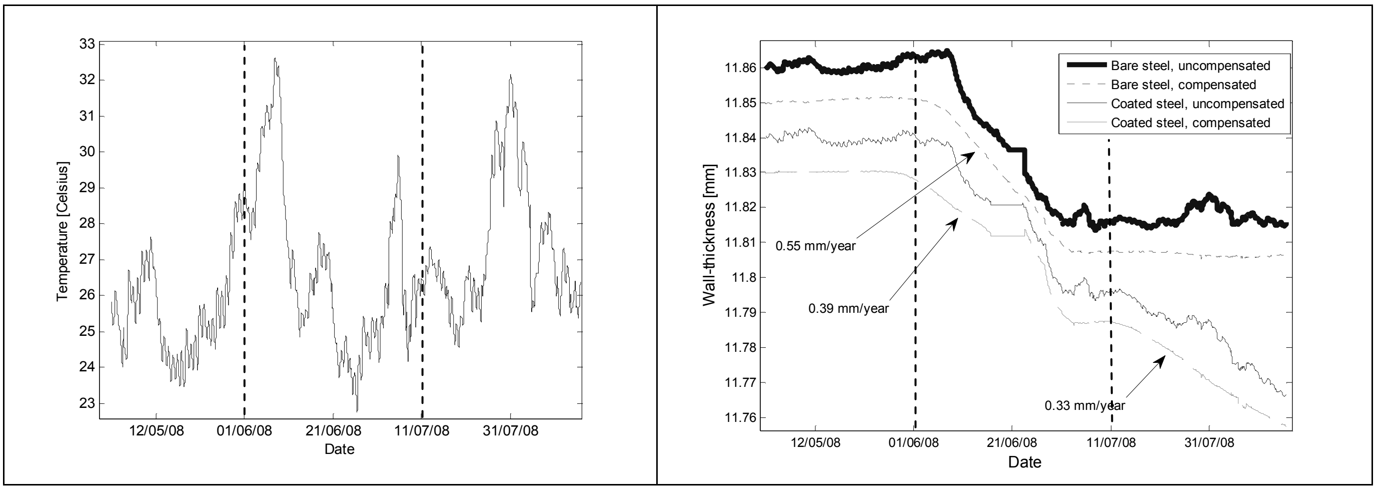

Figure 7 - Measured temperature (to the left) and wall-thickness (to the right) during a 3.5 month period. The wall-thickness measurements are shown with and without temperature compensation for the bare- and coated steel specimen.

Using Eq. (11) one can calculate the standard deviation of the measurements relative to the best fit line. The results are used as input to the Kalman filter for the *R*-parameter and they are shown in Table 2.

Table 2 – Standard deviation of wall-thickness measurements relative to the best fit line. The standard deviation is given both in nanometers (nm) and in picoseconds (ps).

	Standard deviation
Bare steel specimen	5.2 nm/1.75 ps
Powder coated specimen	3.5 nm/1.14 ps

It may be several reasons why the resolution is better for the powder coated specimen, such as small differences in the transducer performance or differences in the surface roughness. The most probable reason, however, is that more acoustic energy is transmitted into the specimen and back when it is powder coated due to better match in acoustic impedance between the water/coating- and coating/steel-interface compared to a water/steel-interface. This is verified both by examining the measured traces and by using the signal model as discussed in the previous section.

During a period of 8 days, the pH in the corrosive liquid was modified in order to investigate how the ultrasound measurements respond to a change in the corrosive environment. The Kalman filter is applied to the dataset for real-time estimation of the corrosion rate. The results are presented in Figure 8 and Figure 9. They show as expected that the estimated corrosion rate increases after event 1 when the pH is decreased from 6.5 to 4. The peak corrosion rates are then 2 and 1.6 mm/year for the bare and coated steel respectively. After event 2, when the pH is decreased from 4 to 3, the peak corrosion rates approaches 3 mm/year for the coated specimen, while it reaches 3.6 mm/year for the bare steel specimen. Only a few hours after the event, the corrosion starts to decrease. This is probably due to rust deposits. After event 3, when the pH is increased from 3 to 4, the estimated corrosion rate decreases down to below 0.5 mm/year for both specimens.

By examining the estimated corrosion rate more carefully one can also notice small variations which are difficult to see directly from the wall-thickness measurements. One of the main features is that the corrosion rate seems to correlate with the temperature; an increase (decrease) in temperature gives an increase (decrease) in the corrosion rate. For the given temperature range, this corresponds well to theory. This should, however, be more carefully investigated before drawing a final conclusion; the correlation may come from small parameter errors in the temperature compensation scheme.

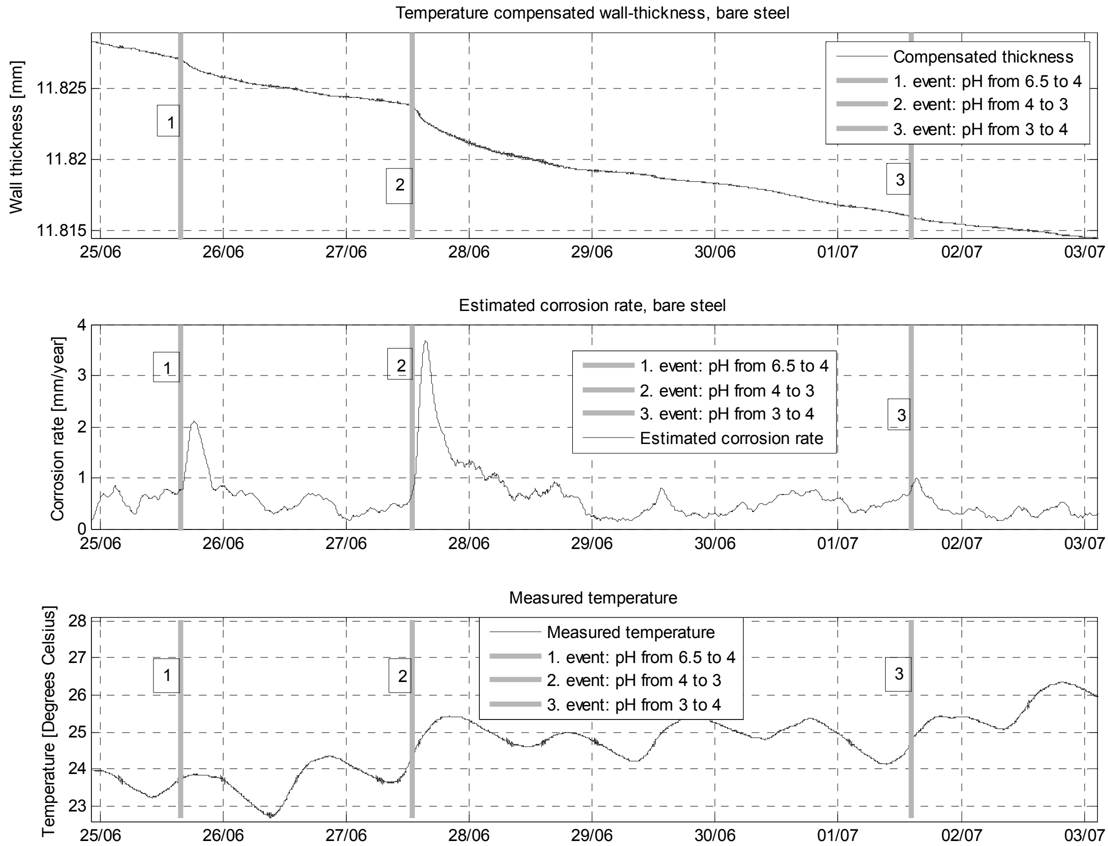

Figure 8 – Wall thickness, estimated corrosion rate and temperature; bare steel.

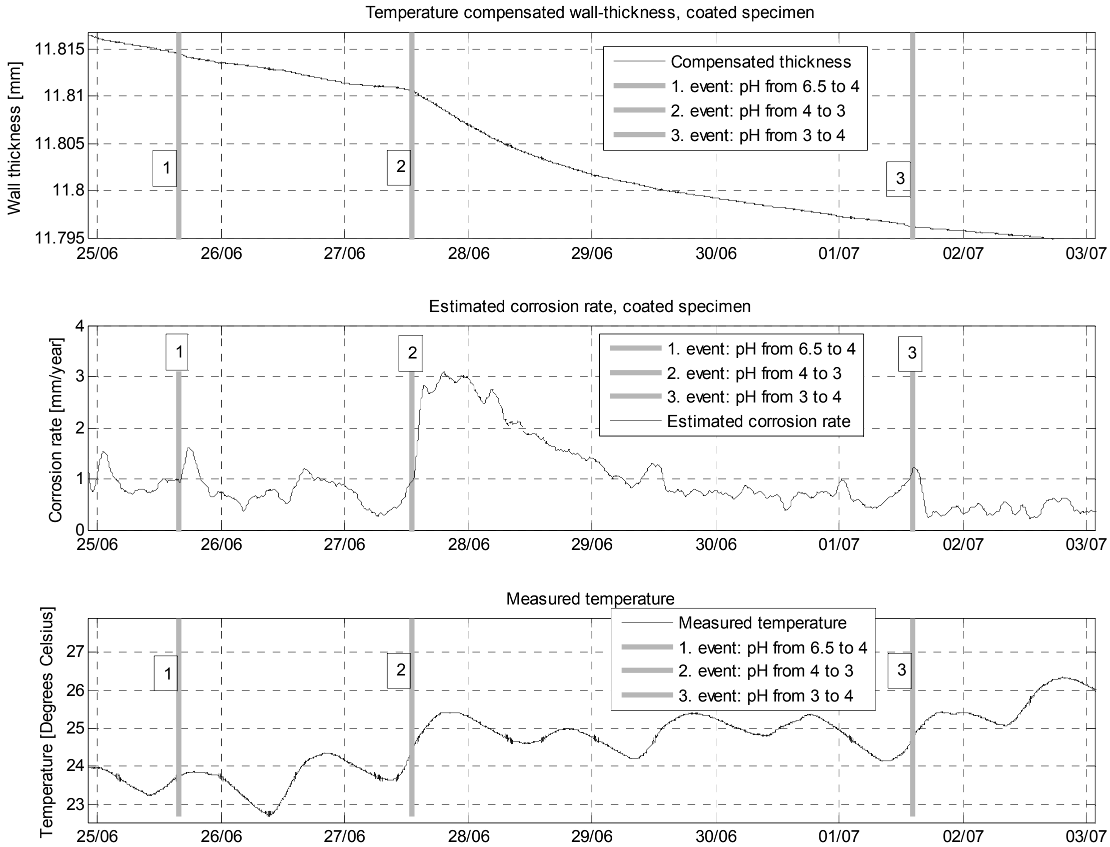

Figure 9 – Wall thickness, estimated corrosion rate and temperature; coated steel.

CONCLUSIONS

The plain wave signal model has been verified against the measured waveforms from the coated specimen by using a genetic algorithm inversion scheme. Further, the signal model is used for examining the received back-wall amplitude as a function of the Q-number and the ratio of *L/λ.* Both the measured- and modeled waveforms show that the amplitude of the back-wall echo is largest from the coated specimen due to the better match in acoustic impedance through the coating. This is in turn the most probable reason why the resolution of the wall-thickness measurements is better for the coated specimen than for the bare steel specimen.

A corrosion experiment has been carried out in order to compare the resolution of ultrasound wall-thickness measurements from bare steel- and coated specimens which while corroding on one side. The results show that the standard deviations of the measurements are 5.2 and 3.5 nm for the bare- and coated steel respectively. Further, a Kalman filter is implemented for real time estimation of the corrosion rate based on temperature compensated wall-thickness measurements. The estimated corrosion rate tracks the changes in the corrosive environment very rapidly. Also it seems that the corrosion rate correlate with the temperature; an increase (decrease) in temperature gives an increase (decrease) in the corrosion rate.

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