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Data-Enabled Quantitative Corrosion Monitoring using Ultrasound

Fangxin Zou[1]

Interdisciplinary Division of Aeronautical and Aviation Engineering, The Hong Kong Polytechnic University, Hong Kong

Abstract – Corrosion is the most pervasive degradation mechanism of engineering infrastructure. It has caused numerous disastrous events that resulted in devastating societal, environmental and financial consequences. There exist numerous standard techniques for corrosion monitoring. Among these techniques, ultrasonic testing stands out as a non-intrusive and straightforward approach. Component wall-thickness loss rate (WTLR) is an intrinsic parameter of corrosion processes. Accurate and rapid determination of WTLRs from continuous ultrasonic wall-thickness loss (WTL) measurements is a critical aspect of effective corrosion control. In this paper, a statistics based method that enables automatic detection of changes in WTLR will be introduced. The detection method further extends the application of ultrasonic corrosion monitoring to more sophisticated corrosion processes that involve multiple rates. Statistical analysis of ultrasonic WTL measurements that were acquired by a state-of-the-art laboratory setup shows that changes in WTLR of 0.1 – 0.2 mm/year can be determined within 1 – 2 hours.

1. Introduction

In 2002, the annual cost of corrosion in the US reached 276 billion dollar [1]. Numerous corrosion induced disasters have occurred in the past, killing thousands of innocent lives and causing severe impact on the environment [2, 3]. Industry has spent much effort on developing and implementing corrosion monitoring in order to minimise the occurrences of adverse scenarios. Since corrosion rate is an intrinsic property of corrosion processes, it is one of the most widely measured reference parameters in corrosion monitoring applications.

Uniform wall-thickness loss (WTL) is the most common corrosion induced degradation mechanism of engineering structures. In such context, it is convenient to express corrosion rate as wall-thickness loss rate (WTLR). Measurement of WTLRs by conventional techniques, such as coupon testing [4-6] and electrochemical testing [7, 8], is not straightforward since these techniques necessitate a number of assumptions (e.g. corrosion area and exact chemical reaction) for converting the intermediate variables that they measure (e.g. mass and electric current) into WTLRs. Also, the fact that they require probes to make direct contact with corrosion environments renders them intrusive for applications in which corrosion takes place inside closed vessels. In contrast, ultrasonic testing is able to make direct wall-thickness measurements, from exteriors of components as well. Recent development in permanently installed transducers greatly improved measurement precision by eliminating the measurement uncertainties associated with manual operation of probes [9-11]. Lately, the author constructed a state-of-the-art ultrasonic corrosion monitoring setup in

[1] Email: frank.zou@polyu.edu.hk.

the laboratory which possesses an unprecedented thickness measurement precision of 20 – 40 nm [12, 13].

Ultrasonic corrosion monitoring results in continuous WTL measurements from which WTLRs can be extracted by linear regression. However, when only a small number of WTL measurements are available, random noise embedded in these measurements gives rise to temporarily scattered WTLRs. In a previous work, the author introduced a statistical approach for quantifying confidence levels of WTLRs that are calculated by linear regression [14]. The analysis procedure is analogue to the probability of detection analysis that is commonly used in non-destructive testing, and detection is called when the confidence level reaches a certain threshold. However, determination of WTLRs by the aforementioned statistical approach requires onset points of changes in WTLR to be known in advance. Such limitation prohibited ultrasonic corrosion monitoring from becoming a fully automatic detection means that is capable of informing changes in WTLR during corrosion processes.

In this paper, an improved statistical method that is able to automatically detect and extract changes in WTLR based on ultrasonic WTL measurements is presented. The method, which builds upon the principle of sequential probability ratio test, scans along WTL measurements to sum up the likelihood that a change in the probability density function of WTLRs has occurred. When the cumulative likelihood attains a certain value, a change in WTLR is defined as detected and the corresponding magnitude is evaluated at the same time. Data analysis with the improved statistical method shows that by using the ultrasonic corrosion monitoring setup constructed by the author, automatic detection of changes in WTLR of 0.1 – 0.2 mm/year can be achieved within 1 – 2 hours. The detection capability and response time demonstrated further promote the ultrasonic setup as an alternative laboratory tool that can be used for carrying out investigations of corrosion processes with varying rates.

2. Materials and Methods

2.1. Ultrasonic Wall-Thickness Loss Measurements

A 10 mm thick mild steel sample (BS 970:1983:080A15, UNS G10160) was subjected to open-circuit corrosion experiments with distilled water, 0.1 M citric acid and 0.1 M acetic acid. The experiments were conducted using the ultrasonic monitoring setup constructed by the author which has a thickness measurement repeatability of ~20 nm over 1 h and that of ~40 nm over 24 h [12]. It is worth mentioning that in order to achieve such measurement repeatability, the effect of temperature on ultrasonic wave velocity needed to be compensated for. Details of the calibration procedure and the compensation strategy can be found in [13]. The ultrasonic setup that was used is illustrated in Figure 1. Figure 2 shows an example of the corrosion site that were resulted from the corrosion experiments.

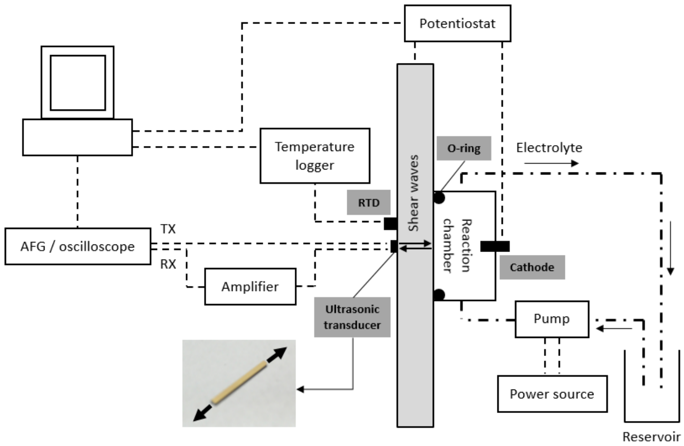

Figure 1 The ultrasonic corrosion monitoring setup that was used to carry out the corrosion experiments [12].

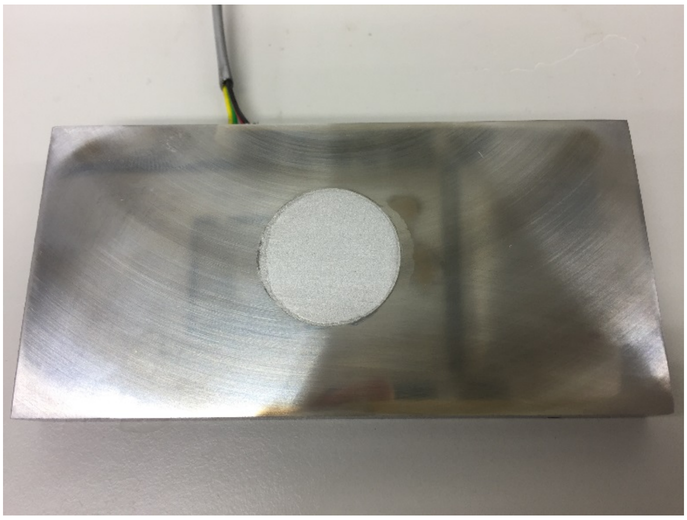

Figure 2 A corrosion site that was induced by the corrosion experiments.

Ultrasonic measurements of the WTLs of the sample are shown in Figure 3. The measurements were acquired at 1-minute intervals. As observed, distilled water had not resulted in any noticeable WTL in the given time frame. In fact, the measurements that were acquired during the experiment with distilled water only demonstrate the noise floor of the ultrasonic measurement system. The two acidic solutions, on the other hand, had caused WTLs in the order of a few microns. Also, during the two acidic corrosion processes, surface passivation led to changes in WTLR at around the 2nd and the 7th hour respectively.

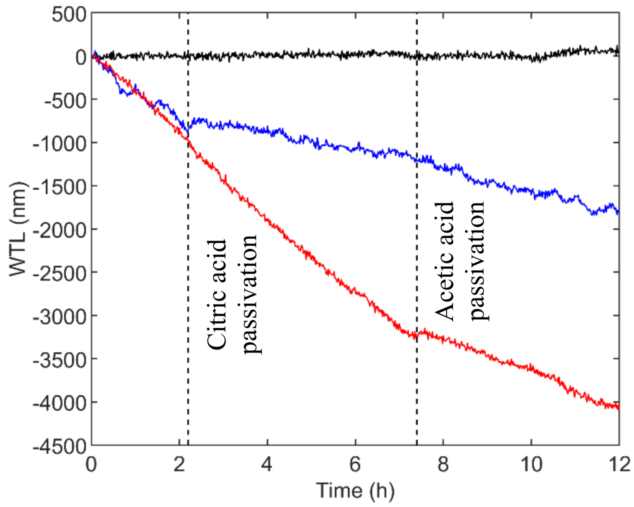

Figure 3 Ultrasonically measured WTLs of the sample during the corrosion experiments with distilled water (black), 0.1 M citric acid (blue) and 0.1 M acetic acid (red).

Although the ultrasonic WTL measurements shown in Figure 3 were sampled at a very high measurement repeatability, they resemble many of the key characteristics of measurements that are normally acquired from field applications. By linear least squares regression, onsets of the changes in WTLR can be conveniently identified retrospectively. However, at the time of occurrence of each of these changes, without a large population of measurements, the presence of noise would introduce much uncertainty to the linearly fitted WTLR and hence it would be difficult to differentiate genuine corrosion progression from measurement uncertainty. Therefore, it is of immediate interest to devise a method for achieving confident on-the-spot detection of changes in WTLR based on ultrasonic WTL measurements. The speed at which a WTLR can be determined is directly related to how quickly one can intervene in a process that is heading in the wrong direction.

2.2.Statistic based Wall-Thickness Loss Rate Detection

Consider a set of N WTL measurements (y) which can be divided into n segments of data according to WTLR (w). The measurements are parameterised by a constant variance of σ^2 and linearly time dependent means of $[c_1 + w_1 t, c_2 + w_2 t, \dots, c_n + w_n t]$. The generalised likelihood ratio (GLR) algorithm [15, 16] is used to quantify changes, with respect to time, in statistical distribution of WTLRs. The accumulated logarithmic likelihood (Z) that a given change in WTLR (η) occurs within a finite measurement subset that is bounded time instants t_j and t_k is calculated by

$$Z_k^j(\eta) = \sum_{i=j}^{k} \frac{2\eta(t_i - t_j)(y_i - c - w_1 t_i) - \eta^2 (t_i - t_j)^2}{2\sigma} \tag{1}$$

where w_1 is the pre-change (or benchmark) WTLR. The change in WTLR is defined as detected at t_k when

$$\max\left(sup\left(Z_k^j(\eta)\right)\right) \geq \ln\left(\frac{1-\beta}{\alpha}\right), \qquad k = 1,2,3,\dots,N, \qquad j = 1,2,3,\dots,k \tag{2}$$

where α is the probability of false-calling (i.e. opposite to confidence level) and β is the probability of non-detection (i.e. opposite to probability of detection). In this work, α and β were set to 0.05 and 0.05 respectively in order to comply with the widely accepted standard of 95/95 (i.e. 95% probability of detection and 95% confidence level). By considering the derivative of $Z_k^j(\eta)$, the value of η that maximises Z_k^j is found to be

$$\eta = \frac{\sum_{i=j}^{k}(t_i - t_j)(y_i - w_1 t_i)}{\sum_{i=j}^{k}(t_i - t_j)^2} \tag{3}$$

An example of the accumulated logarithmic likelihood curves that are used for detecting changes in WTLR is displayed in Figure 4.

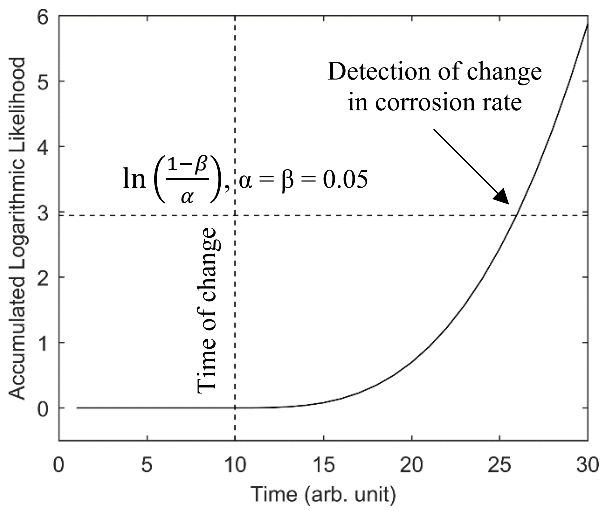

Figure 4 Accumulated logarithmic likelihood curve for changes in WTLR.

The time instant at which a given change in WTLR is detected can also be analytically predicted. The average number (E) of post-change WTL measurements that need to be acquired in order to detect the change is given by [16]

$$E = \left(\frac{2\sigma^2\left(\beta\ln\left(\frac{\beta}{1-\alpha}\right) + (1-\beta)\ln\left(\frac{1-\beta}{\alpha}\right)\right)}{\lambda^2\eta^2}\right)^{\frac{1}{3}} \tag{4}$$

where λ is the sampling interval.

3. Results

The statistical method for detecting changes in WTLR was used to analyse the ultrasonic WTL measurements shown in Figure 3. The mean WTLRs of the two acidic corrosion processes changed at the 140th and the 455th minute respectively due to surface passivation. By linear least squares regressions, the WTLRs were calculated to be ~3 and ~1 mm/year for the pre- and the post-passivation corrosion process with citric acid, and ~4 and ~1.8 mm/year for those with acetic acid. The times of detection for these changes were both calculated by the GLR algorithm based on the experimentally obtained ultrasonic WTL measurements, and predicted by equation (4). The results are given in Table 1. The predictions were attained using the parameters $\sigma = 20,\ 40\ nm, \eta = 2,\ 2.2\ mm/year$ and $\lambda = 1\ min$. The experimental results lie within the predicted values which outline the expected variability. The agreement between the two sets of data suggests that it is also possible to use equation (4) to predict the capabilities of ultrasonic corrosion monitoring systems to detect changes in WTLR.

Corrosion Process	**Change in WTLR (mm/year)**	**Time of Detection (min)**		
		Experimental	**Predicted**	
			σ_w = 20 nm	**σ_w = 40 nm**
Citric acid	~2	7	5.3	8.4
Acetic acid	~2.2	6	4.9	7.9

Table 1 Times of detection for the changes in WTLR recorded.

The detection speeds that are achievable at different WTLRs and different values of measurement repeatability are plotted in Figure 5. It is observed that the higher the WTLR or the measurement repeatability is, the faster the detection will be. Such detectability charts enable users to make more informed decisions when it comes to choosing the right systems for their applications.

The responsiveness to changes in WTLR of the setup constructed by the author ($\sigma = 20,\ 40\ nm$) is also plotted in Figure 5. It can be seen that using the setup constructed by the author, changes in WTLR in the order of 0.1 – 0.2 mm/year, which is of interest to industry, can be confidently detected in less than two hours. This suggests that the ultrasonic setup can become a convenient and efficient laboratory tool for carrying out corrosion rate research.

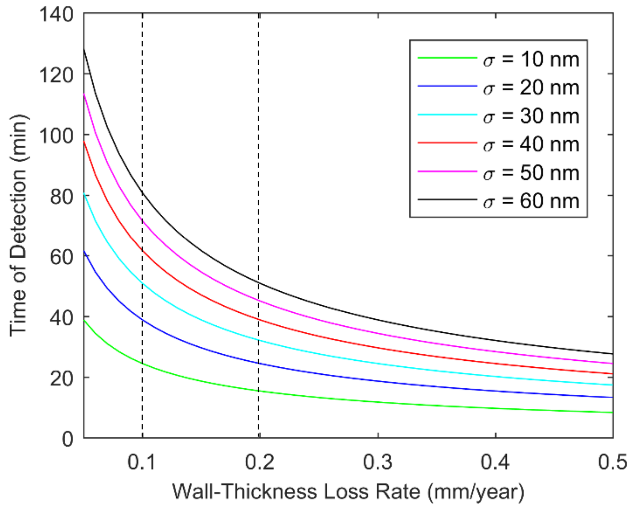

Figure 5 Detectability of changes in WTLR with respect to measurement repeatability. The variability of the detection speeds that are achievable by the setup constructed the author are bounded by the blue and the red curve.

4. Conclusion

In this work, a statistics based approach for automatic detection of changes in WTLR based on ultrasonic WTL measurements is introduced. The effect of measurement noise floor, which makes it difficult to judge confidence of linearly fitted slopes, is mitigated by basing detection on a statistical parameter, namely accumulated logarithmic likelihood, which sums up transient likelihoods of change and, in the meantime, neutralises contributions of random noise. The statistical method was demonstrated through blind detection of changes in WTLR that are embedded in ultrasonic WTL measurements which were acquired by a state-of-the-art laboratory setup during open-circuit corrosion experiments. Detection time computed based on experimental measurements show excellent agreement with analytical predictions, verifying the validity of the statistics based detection method.

The method was further used to assess the measurement capability of the ultrasonic corrosion monitoring setup which was constructed by the author in a previous work. It is demonstrated that detection times in the range of 1 – 2 hours can be achieved for changes in WTLR that are of significant importance to industry (i.e. 0.1 – 0.2 mm/year). Equipping the ultrasonic setup constructed by the author with the statistics based detection method potentially allows ultrasound to be used for high-precision laboratory investigations of corrosion processes that involve variable WTLRs.

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