ESTIMATION OF FLOW-ACCELERATED CORROSION (FAC) RATE FROM NOISY WALL THICKNESS MEASUREMENT DATA

D. Lu, M.D. Pandey
University of Waterloo, Waterloo, ON, Canada, N2L 3G1
E-mail of corresponding author: mdpandey@uwaterloo.ca

ABSTRACT

The piping system in the reactor coolant pressure boundary experiences flow-accelerated corrosion (FAC), which can have adverse impacts on the structural integrity. In the fitness-for-service (FFS) assessment, the future wall thickness of the tubing is predicted based on the latest wall thickness and estimated FAC growth rate. If the wall thickness predicted at the end of evaluation period does not meet the specified acceptance criteria, the pipe section needs to be removed from the service. In this context, the FAC rate is the most important element of the FFS assessment. However, accurate estimation of FAC growth rate is confounded by the sizing error associated with inspection probes (such as ultrasonic probes) used for the wall thickness measurement. Therefore, this paper presents a sound probabilistic method for estimating the FAC rate given the repeated noisy measurements of wall thickness of a sample of pipes taken during plant outages.

INTRODUCTION

General Background

The reactor heat transport system consists of vast piping system, in which the flow accelerated corrosion (FAC) is a common degradation mechanism that is seen in the areas of high turbulence or change in flow velocity. To ensure the fitness-for-service of piping system, periodic inspections are carried out to measure the remaining wall thickness using ultrasonic probes and estimate the FAC rate that is needed to predict the end of life of the component. The nuclear industry in Canada and the U.S. has undertaken extensive research to develop fitness for service criteria and guidelines for inspection and maintenance of nuclear power plant components [1-3].

The piping wall thickness measurement data suggest that the FAC rate tends to be highly variable across the population of pipe bends, which confounds the prediction of end of life of pipes in uninspected population. Furthermore, the actual FAC rate in inspected pipes is hard to quantify due to sizing error associated with the inspection tool. The sizing error is a result of (1) limited resolution and signal to noise ratio associated with the probes, and (2) subjectivity associated with the data interpretation, such as calibration curves. The sizing error is also referred to as noise in signal processing literature. The sizing error is not a fixed and known quantity; rather its magnitude varies each time a new measurement is taken. Because of the random nature of sizing error, true wall thickness is never known with high precision, such that growth rate estimated without proper processing of measured data will lead to erroneous predictions. Accurate estimation of the growth rate is important. The reason is that a conservative prediction of growth rate will lead to frequent inspection/maintenance outages resulting in loss of efficiency, whereas a non-conservative prediction may lead to non-compliance with safety standards.

The main objective of this paper is to develop a sound probabilistic method for the estimation of the probability distribution of degradation growth rate from noisy measurement data, i.e., the data that are contaminated by random sizing error introduced by an inspection probe.

TECHNICAL PROBLEM

Basic Model

The FAC process causes wall thickness loss in the pipe bend section, as shown in Fig. 1. The corrosion is typically localized in form of a patch, also referred to as a flaw in this paper, in which the wall thickness loss continues to increase over time. In case of FAC, it is seen that the corrosion rate for a specific section remains reasonably constant, while the growth rates of different pipe sections vary greatly across the population. In such cases, the FAC rate in the population can be modeled as a random variable R with density function $f_R(r)$. The FAC rate for a specific section is then a realization from the distribution of R and it is a constant over time. Suppose $x(t)$ denotes the amount of degradation or actual size of a flaw at time t, a commonly used liner degradation model can be written as

$$x(t) = rt. \tag{1}$$

where r is the growth rate of this specific section.

At the population level, the degradation at time t is considered as a random variable, $X(t)$, also given by the following linear law:

$$X(t) = Rt. \tag{2}$$

This model is generally referred as the random rate model [4]. Again, the basic assumption here is while the FAC rates vary across a population of components, it is constant for a specific pipe over time. If pipe specific FAC rate is expected to vary over time, then a stochastic process model, such as gamma process, is required to model the degradation growth.

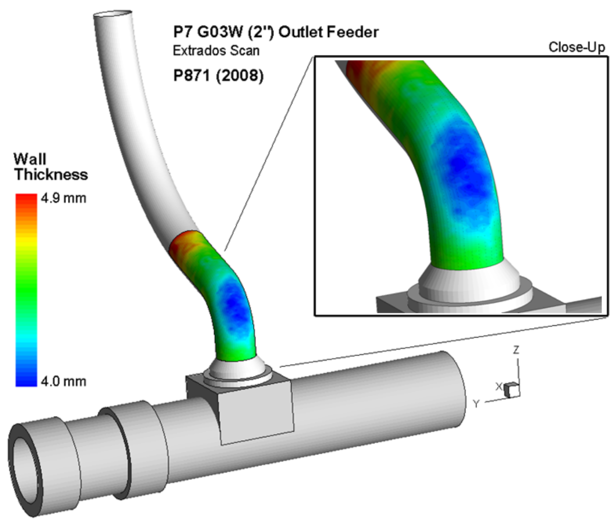

Fig. 1: Flow accelerated corrosion (FAC) of a pipe bend.

Effects of Sizing Error

In general notation, the size of the i^{th} flaw at time t_{ij} is denoted as x_{ij}. Suppose actual size of the i^{th} flaw takes the values $x_{i1}, x_{i2}, \cdots, x_{im_i}$ at times $t_{i1}, t_{i2}, \cdots, t_{im_i}$, respectively. Here m_i is the number of measurements of the i^{th} flaw taken at different inspection outages. From previous discussion, it follows that the actual (or true) growth rate of degradation in this flaw remains a constant (r_i), and it can be evaluated as follows:

$$r_i = \frac{x_{i2} - x_{i1}}{t_{i2} - t_{i1}} = \frac{x_{i3} - x_{i2}}{t_{i3} - t_{i2}} = \cdots = \frac{x_{ij} - x_{i,j-1}}{t_{im_i} - t_{i,m_i-1}}. \tag{3}$$

The flaw growth rate distribution of a population of components can then be obtained by fitting all the flaw specific rates r_i with an appropriate distribution.

However, in reality an inspection probe adds a random noise to actual flaw size $x_i(t)$, such that the measurement of the flaw size has to be conceptually treated as a random variable $Y_i(t)$, defined as

$$Y_i(t) = x_i(t) + E. \tag{4}$$

where E is the random sizing error characterized by distribution density function $f_E(e)$.

Any specific measured size of this flaw y_{ij} at time t_{ij} is a realization from the distribution of $Y_i(t_j)$. Suppose a series of measurements of the i^{th} flaw were taken as $y_{i1}, y_{i2}, ..., y_{im_i}$ at times $t_{i1}, t_{i2}, ..., t_{im_i}$, respectively. The measured growth rate at the j^{th} inspection, r_{Mij}, can be calculated as:

$$r_{Mi2} = \frac{y_{i2} - y_{i1}}{t_{i2} - t_{i1}}, r_{Mi3} = \frac{y_{i3} - y_{i2}}{t_{i3} - t_{i2}}, ..., r_{Mim_i} = \frac{y_{ij} - y_{i,j-1}}{t_{im_i} - t_{i,m_i-1}} \tag{5}$$

It is clear that the measured growth rates, r_{Mij}, are not equal to actual growth rate r_i, and they are likely to fluctuate due to effect of random sizing error. In addition, the measured rates can also be negative, even though the underlying growth rate is always positive. The departure between the measured and actual rate will increase with the increase in variability associated with the sizing error, E. Fig. 2 illustrates conceptually the variation of measured sizes about the actual growth curve.

It should be recognized that given a set of inaccurate or noisy measured sizes, $y_{i1}, y_{i2}, ..., y_{im_i}$, for an i^{th} flaw, the underlying growth rate of the flaw (r_i) cannot be determined exactly. It can be only estimated in distribution.

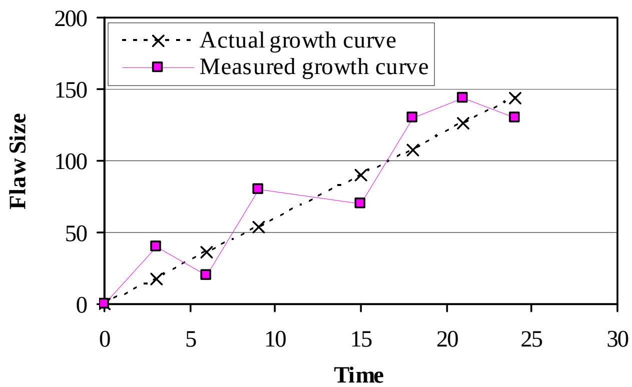

Fig. 2: Illustration of actual growth curve and measurements of degradation in the i^{th} flaw

A common approach to estimate growth rate is to use linear regression method [3] to correlate measurements (y_{ij}) with time (t_{ij})for a particular i^{th} component as

$$y_{ij} = \beta_{i0} + \beta_{i1} t_{ij} + \epsilon, \tag{6}$$

where β_{i0} and β_{i1} are regression coefficients, and ϵ is error of regression, which is a normally distributed random variable with zero mean and some standard deviation. The slope, β_{i1}, can be interpreted as degradation rate for this particular flaw. However, for many piping systems in nuclear plants, the number of repeated measurements for a component is usually less than 3 or 4. Because of limited data, the regression slope, β_{i1}, cannot be estimated with a high degree of confidence.

PROPOSED METHOD

At the outset, FAC related degradation is absent and suppose that incubation time for FAC negligible. Then, the measured degradation can be written as:

$$Y_{ij} = x_{ij} + E_{ij} = r_i t_{ij} + E_{ij} \quad j = 1, 2, \cdots, m_i, \tag{7}$$

where m_i is the number of inspections completed for the *i*th flaw. The measurement error E_{ij} are taken as independent and identically distributed (i.i.d.) normal random variables with mean μ_E and standard deviation σ_E.

Since x_{ij} are constants, Y_{ij} are independent and normally distributed random variables. The mean and standard deviation of Y_{ij} are $(\mu_E + r_i t_{ij})$ and σ_E respectively, i.e., $Y_{ij} \sim \phi(\mu_E + r_i t_{ij}, \sigma_E^2)$. Note that $\phi(x; \mu, \sigma^2)$ denotes the probability density function (PDF) of a normal random variable with mean μ and standard deviation σ. The PDF of Y_{ij} is

$$f_{Y_{ij}}(y_{ij}) = \frac{1}{\sqrt{2\pi\sigma_E^2}} \exp\left[-\frac{(y_{ij} - \mu_E - r_i t_{ij})^2}{2\sigma_E^2} \right]. \tag{8}$$

The distribution of Y_{ij} has three parameters, namely, μ_E, σ_E, and r_i. Since parameters of the noise distribution are known, there is a single unknown parameter r_i that needs to be estimated. The maximum likelihood (ML) method can be used for the estimation. Denote all the repeat measurements over time of a specific i^{th} flaw by $\mathbf{y}_i = \{y_{i1}, y_{i2}, \cdots, y_{im_i}\}$. Since $\mathbf{y}_i$ are samples from independent random variables, the likelihood function of r_i given measured data $\mathbf{y}_i$ is

$$\begin{aligned} f_i(\mathbf{y}_i; r_i) &= \prod_{j=1}^{m_i} f_{Y_{ij}}(y_{ij}) \\ &= \prod_{j=1}^{m_i} \frac{1}{\sqrt{2\pi\sigma_E^2}} \exp\left[-\frac{(y_{ij} - \mu_E - r_i t_{ij})^2}{2\sigma_E^2}\right] \quad (r_i > 0). \end{aligned} \tag{9}$$

By maximizing Eq. (9) with respect to α, a maximum likelihood estimation (MLE) of the flaw specific growth rate can be obtained.

Achterbosch and Grzelak [5] proposed that MLE should be applied to each set of flaw specific measurements resulting in a sample of MLE of growth rates $r_i, i = 1, 2, \cdots N$. By fitting a probability distribution to this sample, population distribution of growth rate should be obtained. This is a conceptually imprecise approach. The reason is that MLE of r_i is expected to have large confidence interval (or variability) due to use of a few measurements (3 or 4) for each flaw. So MLE estimates do not constitute a random sample of r_i from which the distribution of growth rate can be reliably estimated.

We propose a single application of MLE for the estimation of parameters of the growth rate distribution by adopting a *hierarchical* thinking. In the hierarchical model, the measured sizes, $\mathbf{y}_i$, are normally distributed with the growth rate r_i as a parameter; while r_i itself follows the distribution $f_R(r; \theta)$, and θ denotes the distribution parameters. Thus, the likelihood function given measured sizes has to be maximized with respect to θ for its direct estimation.

Using theorem of total probability, the marginal likelihood function of θ given measured sizes $\mathbf{y}_i$ can be obtained as

$$\begin{aligned} f_i(\mathbf{y}_i; \theta) &= \int_0^\infty f_i(\mathbf{y}_i; r_i) f_R(r; \theta) \mathrm{d}r \\ &= \int_0^\infty \prod_{j=1}^{m_i} \frac{1}{\sqrt{2\pi\sigma_E^2}} \exp\left[-\frac{(y_{ij} - \mu_E - r_i t_{ij})^2}{2\sigma_E^2}\right] f_R(r; \theta) \mathrm{d}r. \end{aligned} \tag{10}$$

Now the likelihood for sample of *n* flaws can be written as a product of the likelihood for the individual flaws, as written in following Eq. (11).

$$f(\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_n; \theta) = \prod_{i=1}^{n} f_i(\mathbf{y}_i; \theta). \tag{11}$$

The product can be written, because growth rate in each pipe is assumed to be independent of the other pipes. The sizing error is always independent for every measurement. Finally, parameters θ can be estimated by maximizing Eq. (11) and the population flaw growth rate distribution is obtained, which is an important indicator of the overall degradation of a group of components and also the flaw growth rate estimation for the un-inspected components.

For the flaw specific growth rate of inspected components, its actual value is masked by the sizing error and should be estimated as a distribution. After the population growth rate distribution is obtained, the flaw specific rate has a conditional probability distribution. Denote the flaw specific rate estimation for the i^{th} flaw as a random variable R_i, $R_i = [R|\mathbf{y}_i]$. Using the Bayesian theorem, the PDF of R_i is

$$f_{R_i}(r_i; \theta) = f_{R|\mathbf{Y}_i}(r_i|\mathbf{y}_i; \theta) = c f_i(\mathbf{y}_i; r_i) f_R(r_i; \theta), \tag{12}$$

where $f_i(\mathbf{y}_i; r_i)$ the likelihood function of the flaw specific rate given inspection data and is given by Eq. (9); c is the normalization constant:

$$c = \frac{1}{\int_0^\infty f_i(\mathbf{y}_i; r_i) f_R(r_i; \theta)}. \tag{13}$$

The estimated population flaw growth rate distribution and flaw specific growth rate can then be used in further for predicting remaining lifetime or future flaw size growth of both inspected and un-inspected components.

CASE STUDY

Data

This section presents a case study regarding the flow accelerated corrosion (FAC) of feeder pipes in the heat transport system of a nuclear plant. The system consists of 114 pipes of 2" diameter, and 107 of them were inspected for the first time at 17.08 effective full power year (EFPY) or at 18.4 EFPY. 26 pipes were inspected twice. The data consists of minimum pipe wall thickness near the first weld, which is close to the outlet end fitting. The wall thickness was measured using a set of 6 ultrasonic probes. The initial wall thickness is 6.5 mm as per the design. The measurement error of the probe is assumed to be normal distributed with zero mean and standard deviation of 0.25 mm (about 4% of initial wall thickness). A histogram of the latest wall thickness measurements is shown in Fig. 3.

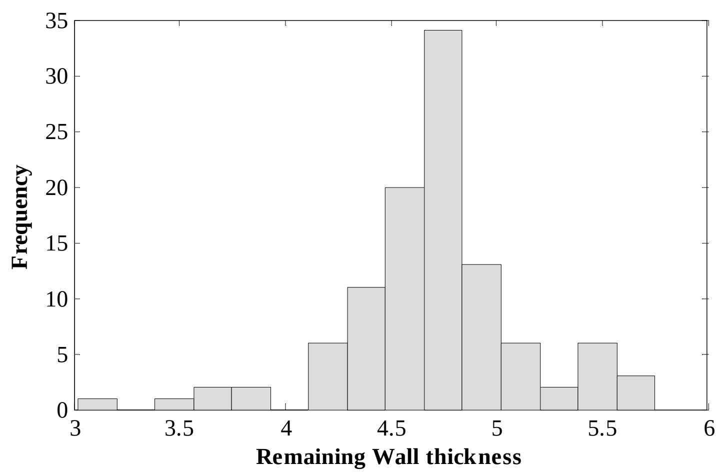

Fig. 3: Histogram of the measurements of minimum pipe bend wall thickness

Parameter estimation

Lognormal distribution is assumed as the flaw growth rate distribution of the feeder pipe population. The PDF of the lognormal distribution is

$$f_X(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right), \quad x > 0 \tag{14}$$

where μ and σ are parameters of the lognormal distribution.

Two methods are applied for the parameter estimation: (1) the proposed MLE method; (2) a naive (or simple) method in which the sizing error is ignored and sample of measured rates, as defined by Eq.5, are used to estimate the growth rate distribution. The results are given in Table 1 and Fig. 4.

As can be seen from the results, the proposed method and the naïve method result in close estimates of the average growth rate of the population. But the standard deviation by the simple method is larger than that by the proposed MLE method, since the simple method includes the noise.

Table 1: Estimated parameters of lognormal FAC rate distribution

Method	Parameters	Average	Standard deviation
Proposed MLE	$\mu = -2.30$, $\sigma = 0.19$	0.10 mm/EFPY	0.019 mm/EFPY
Naive method	$\mu = -2.32$, $\sigma = 0.24$	0.10 mm/EFPY	0.025 mm/EFPY

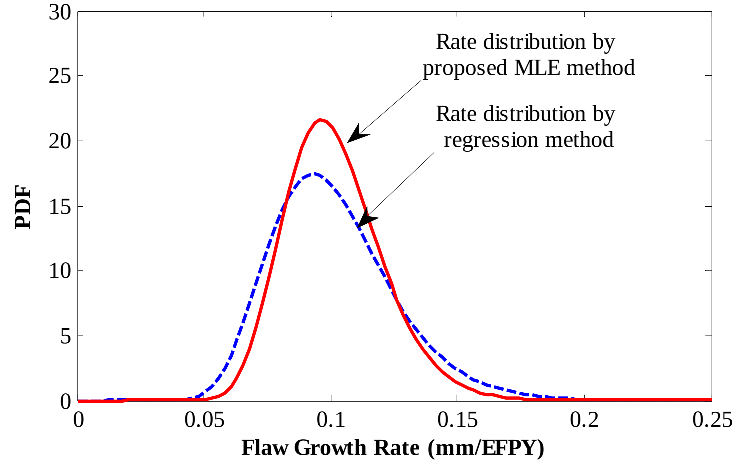

Fig. 4 Rate distribution by the proposed MLE method (solid line) and naïve method (dashed line)

Pipe Specific FAC Rate

Instead of assigning only a single number to the pipe specific FAC rate, as in the naive method, the proposed MLE method leads to a distribution, given by Eq. (12). As an example, the pipe specific FAC rates of two pipes, denoted as pipe A and B, are calculated. The measured wall thickness data of pipe A and B are given in Table 2. The estimated FAC rate distributions for the two pipes are presented in Fig. 5 along with the population distribution for sake of comparison.

Table 2: Measured wall thickness of pipes A and B

Insp. time(EFPY)	14.63	16.38	17.95
Pipe A (mm)	N.A.	4.97	4.68
PIpe B (mm)	4.63	4.33	4.50

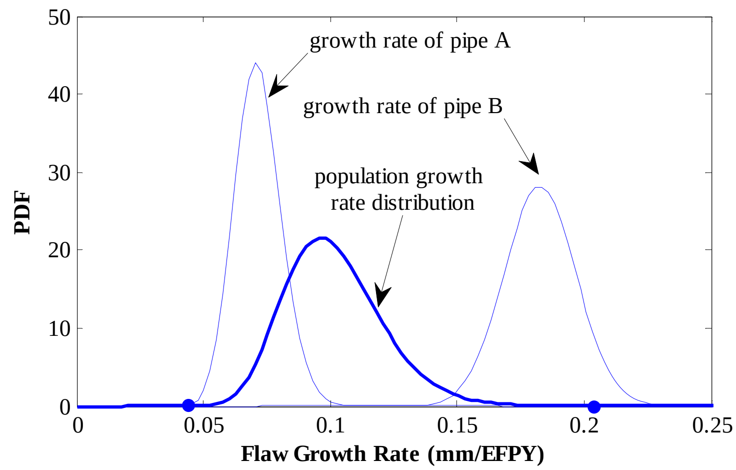

Fig. 5: Rate distribution of pipe A and pipe B compared to the population growth rate distribution (cicrcles on X axis denote the measured rates for these pipes)

From the pipe specific rate distribution, remaining lifetime distribution of each pipe can be easily derived. Suppose the initial wall thickness is w and the minimum required wall thickness is c ($w > c$). The lifetime of the i^{th} pipe, denoted as T_i, is given by $T_i = (w - c)/R_i$, where R_i is the FAC rate of the i^{th} pipe. The cumulative distribution function (CDF) of T_i can be written as

$$\begin{aligned} F_{T_i}(t) &= \Pr[T_i \le t] = \Pr[R_i > (w-c)/t] \\ &= 1 - F_{R_i}((w-c)/t). \end{aligned} \tag{15}$$

The PDF of T_i can be subsequently written as

$$\begin{aligned} f_{T_i}(t) &= \frac{\mathrm{d}F_{T_i}(t)}{\mathrm{d}t} = \frac{\mathrm{d}\left[1 - F_{R_i}((w-c)/t)\right]}{\mathrm{d}t} \\ &= \frac{w-c}{t^2} f_{R_i}\left(\frac{w-c}{t}\right). \end{aligned} \tag{16}$$

Given the initial wall thickness of 6.5 mm and c = 2.41 mm, the lifetime distributions of pipes A and B and that of an un-inspected pipe are shown in Fig. 6. Note that for an un-inspected pipe, the lifetime distribution can be calculated from the population rate distribution of R.

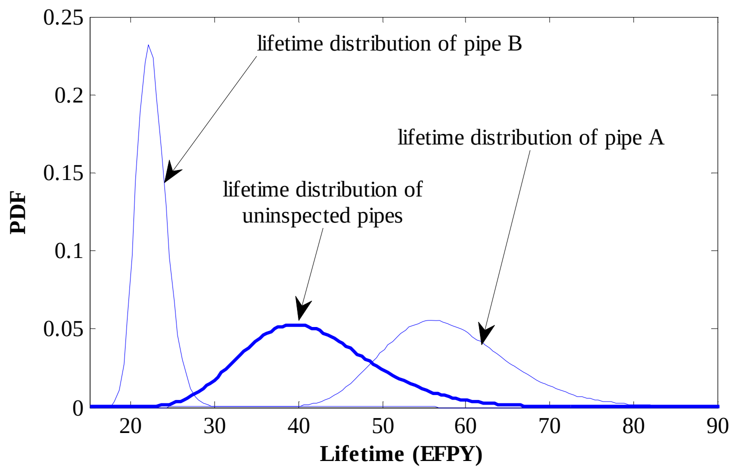

Fig. 6: Lifetime distribution of pipe A and pipe B, compared with un-inspected pipes

SUMMARY

In this paper, a probabilistic method is presented for the estimation of degradation growth rate based on the noisy data. The growth rate distribution can be customized to each component of the population based on component specific measurements. The proposed method uses all the available data and accounts for sizing errors with a sound statistical reasoning.

A practical case study is presented that analyzes the FAC rate distribution in the feeder pipes of a nuclear reactor. The feeder pipes supply primary coolant from the reactor core to steam generators. The proposed method is generic and it can be used to analyze rate of any time-dependent degradation process for which only noisy measurements are available, such as fretting wear in steam generator tubing.

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