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Demonstration of probability of detection taking consideration of both the length and the depth of a flaw explicitly

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ABSTRACT

This study proposes the construction of the probability of detection (POD) as a function of both the depth and length of a flaw. In addition, this study discusses how to censor signals in constructing the POD. The general effects of the flaw parameters on signals are evaluated by numerical simulations, and the scattering of signals, which is critical to the POD, is estimated by signals obtained in experiments. A new likelihood function is introduced, and the proposed method is demonstrated using eddy current signals caused by various artificial flaws on a flat type 316L stainless steel plate obtained in a laboratory test. The demonstration confirms that the proposed method can provide a reasonable POD with a small amount of experimental signals, and reveals that proper censoring significantly decreases the detrimental effect of noise on the POD.

1. Introduction

Periodic non-destructive inspection is critical to assure the safety and reliability of structures. Harmful flaws must be detected and suitable actions should be taken based on their effect. However, attempting to detect insignificant flaws that do not affect the integrity of structures would lead to an unnecessary burden. Therefore, the practical capability of a non-destructive testing method should not be evaluated based on the minimum size of a flaw that the method can detect, but instead it should be evaluated for its capability to detect flaws that must be detected. In contrast, there are many factors affecting the capability of non-destructive testing methods, which makes the capability rather probabilistic in practice.

In the aerospace industry, the probability of detection (POD) concept was proposed in the 1980s and has been successfully used since that time to address this issue [1,2]. The main concept of a POD is to express the probability that a flaw with a size of a is detected using a probabilistic function, POD(a), to quantify the capability of a non-destructive testing method. The POD contributes not only to the quantification of non-destructive testing methods but also to the risk-based maintenance [3,4]. A challenge associated with constructing a reliable POD has been the difficulty in preparing a sufficient number of flaws to satisfy statistical significance. Recent developments in computers and computational physics have demonstrated that a so-called "model-assisted POD" can replace some experimental measurements to construct a POD with numerical simulations [5]. Consequently, the POD has the focus of more attention in recent years. However, the application of POD in non-aerospace industries is limited, even in case of the nuclear industry whose safety and reliability requirements are as rigorous as those of the aerospace industry [6].

A previous study noted that a major reason for this limitation is that a conventional POD assumes that a flaw is characterized by just one parameter. Because usually more than one flaw parameter has large effect on signals, characterizing a flaw by just one parameter makes accurately evaluating POD difficult. Furthermore, the effect of a flaw on structural integrity is usually evaluated on the basis of the length and the depth of the flaw, which indicates that it is preferable that POD is given as a function of these flaw parameters from the viewpoint of maintenance of structures. These motivated the study to propose the evaluation of a POD as a function of multiple parameters [7]. The main idea of the proposed method was to evaluate the mean and standard deviation of the probability using simulated and experimental data, respectively. The method does not postulate the closed-form of the mean as a function of flaw parameters, and enables construction of a POD using data that does not satisfy linearly or constant variance requirements. Although the study demonstrated that the proposed method could provide a POD with its confidence bounds as a function of the depth and length of a flaw using eddy current signals, all the signals were obtained in three-dimensional finite

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element simulations. In addition, managing noise-polluted data, which is indispensable to deal with actual signals, was not discussed.

Therefore, building on previous research, the present study presents a method to construct a practical POD as a function of both the depth and length of a flaw, and demonstrates that method using experimental data. This study also discusses how to censor data, which is especially important for signals buried with noise, and the developed method is demonstrated using eddy current signals gathered in laboratory experiments.

2. Proposal of a POD model

This study proposes a method that assumes that numerical simulations can evaluate signals due to a flaw with a known profile, and the amplitude of signals due to a flaw with a depth of d and a length of l in practical measurements, $V(d,l)$, is given as

$$V(d,l) = N(\mu_1,\ \sigma_1^2) \times V^{sim}(d,l) + N(\mu_2,\ \sigma_2^2) \tag{1}$$

where $V^{sim}(d,l)$ is the amplitude of signals obtained by numerical simulations, and $N(\mu,\ \sigma^2)$ represents a normal distribution with a mean of μ and a standard deviation of σ. Normal distributions were assumed to account for the probabilistic nature of non-destructive testing signals because it is the most general distribution. The two normal distributions, $N(\mu_1, {\sigma_1}^2)$ and $N(\mu_2, {\sigma_2}^2)$, are used on the basis of an assumption that in general the effects of flaw characteristics that are not explicitly parameterized, noise that the numerical simulations cannot consider, and so on, are categorized into those relevant and irrelevant to flaw signals.

Eq. (1) indicates that $V(d,l)$ is regarded as another normal distribution whose mean, μ, and standard deviation, σ, are $\mu = \mu_1 V^{sim}(d,l) + \mu_2$ and $\sigma = (V^{sim}(d,l)^2\ {\sigma_1}^2 + {\sigma_2}^2)^{1/2}$, respectively. Therefore, the four parameters in the above equation, μ_1, σ_1, μ_2, and σ_2, are estimated based on actual measured signals, V_i, using a maximum likelihood analyses. It should be noted that, in reality, a signal due to a tiny flaw is buried in noise or that due to a large flaw becomes larger than the maximum output of an instrument. Such signals must be censored and treated differently because the information contained in such signals is less quantitative. In the same manner as in conventional $\hat{a}$ vs a analyses [1,8], this study evaluates the probability that 'a signal becomes smaller than a certain value' or 'a signal becomes larger than a certain value' rather than 'a signal becomes the certain value' to deal with such signals.

The log-likelihood function of the maximum likelihood analyses, on the basis of the discussion above, is given as

$$\begin{aligned} \ln L = & \sum_{i=1}^{M_l} \ln \Phi\left(\frac{V_l - \left(\mu_1 V^{sim}(d_i,l_i) + \mu_2\right)}{\sqrt{V^{sim}(d_i,l_i)^2\sigma_1^2 + \sigma_2^2}}\right) \\ & -\frac{1}{2}\sum_{i=M_l+1}^{M-Mr}\left[\ln\left\{2\pi\left(V^{sim}(d_i,l_i)^2\sigma_1^2 + \sigma_2^2\right)\right\} + \frac{\left\{V_i - (\mu_1 V^{sim}(d_i,l_i) + \mu_2)\right\}^2}{V^{sim}(d_i,l_i)^2\sigma_1^2 + \sigma_2^2}\right] \\ & + \sum_{i=M-M_r+1}^{M} \ln\left(1 - \Phi\left(\frac{V_r - \left(\mu_1 V^{sim}(d_i,l_i) + \mu_2\right)}{\sqrt{V^{sim}(d_i,l_i)^2\sigma_1^2 + \sigma_2^2}}\right)\right) \end{aligned} \tag{2}$$

where d_i and l_i are the depth and length of the flaw that provided V_i, respectively, and Φ denotes the cumulative distribution function of the standard normal distribution function. The measured signals are assumed to be in ascending order; and the total number of signals is denoted as M; and M_l and M_r are the numbers of signals regarded as'buried with noise' and 'saturated', respectively. The thresholds of the left- and right-censors are set as V_l and V_r.

Table 1
Measured signals used to construct the POD.

ID	Profile	Depth, d [mm]	Length, l [mm]	Signal, V [V]
1	Half-ellipse	0.3	20	0.44
2	Rectangular	0.5	20	0.65
3	Half-ellipse	0.5	20	0.66
4	Half-ellipse	0.5	3	0.70
5	Half-ellipse	0.5	5	0.75
6	Half-ellipse	0.5	20	0.76
7	Rectangular	0.5	10	0.85
8	Half-ellipse	0.5	20	0.88
9	Half-ellipse	0.5	10	0.93
10	Half-ellipse	1	3	1.03
11	Half-ellipse	1	5	1.55
12	Half-ellipse	1	20	1.75
13	Half-ellipse	3	3	1.77
14	Half-ellipse	1	10	1.96
15	Rectangular	1	20	1.98
16	Half-ellipse	5	3	2.08
17	Half-ellipse	1	20	2.08
18	Rectangular	1	10	2.11
19	Half-ellipse	1.5	20	3.15
20	Half-ellipse	3	5	3.56
21	Half-ellipse	5	5	4.30
22	Half-ellipse	2.5	10	5.15
23	Rectangular	2.5	10	5.41
24	Half-ellipse	2.5	20	5.49
25	Half-ellipse	3	20	5.86
26	Half-ellipse	5	10	7.11
27	Rectangular	5	10	7.45
28	Half-ellipse	5	20	7.61
29	Rectangular	5	20	8.08
30	Half-ellipse	5	20	8.20
31	Half-ellipse	10	20	9.72

After the parameters are obtained, the POD, as a function of the depth and length of a flaw, is obtained as a probability that $V(d,l)$ exceeds a given threshold, V_{th}, as

$$\mathrm{POD}(d,l) = \Phi\left(\frac{\left(\mu_1 V^{sim}(d,l) + \mu_2\right) - V_{th}}{\sqrt{V^{sim}(d,l)^2\sigma_1^2 + \sigma_2^2}}\right). \tag{3}$$

It should be noted that Eq. (3) explicitly deals with the depth and length of a flaw and thus the POD is obtained as curves in a two-dimensional plane. The confidence bounds of Eq. (3) is evaluated using a bootstrap calculation [9]. This study conducted 1000 bootstrap calculations to obtain the confidence bounds, which took approximately 3 min using R running on an ordinary Windows PC.

3. Demonstration of the proposed model

3.1. Signals used for the demonstration

This study used eddy current signals gathered in laboratory tests to demonstrate the proposed model. The slits were created using electro-discharge machining and had a width of approximately 0.5 mm. Other specifications of the slits are summarized in Table 1, together with the amplitude of their maximum signals. The signals were gathered using a plus point probe with a height, length, and width of 10, 10, and 3.6 mm, respectively. The exciting frequency was 200 kHz. The probe was attached to an XY stage and scanned the surface of the plates two-dimensionally with a pitch of 1 mm and a lift-off of 0.5 mm. The lift-off, which was manually set using a Vernier scale, was intentionally set not to be very accurate to simulate practical noise. In addition, the probe was accelerated and decelerated rather quickly when it moved to