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Probabilistic evaluation of detection capability of eddy current testing to inspect pitting on a stainless steel clad using multiple signal features

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Abstract. This study proposes a probability of detection (POD) model to quantitatively evaluate the capability of eddy current testing to detect flaws on the inner surface of pressure vessels cladded by stainless steel and in the presence of high noise level. Welded plate samples with drill holes were prepared to simulate corrosion that typically appears on the inner surface of large-scale pressure vessels. The signals generated by the drill holes and the noise caused by the weld were examined using eddy current testing. A hit/miss-based POD model with multiple flaw parameters and multiple signal features was proposed to analyze the measured signals. It is shown that the proposed model is able to more reasonably characterize the detectability of eddy current signals compared to conventional models that consider a single signal feature.

Keywords: POD, multi-parameter, weld, corrosion, pressure vessel

1. Introduction

Pressure vessels are common and essential components in many industries, and require high strength and high corrosion resistance to internal fluids. To this end, the inner surface of a pressure vessel is often cladded by austenitic stainless steel, which is susceptible to corrosion in the presence of chloride ions [1-3]. For this reason, when fluids containing chloride ions flow into a pressure vessel, intensive inspections are required to confirm the integrity of the inner surface of the pressure vessel.

Eddy current testing (ECT) is one of the most suitable methods for this purpose because of its remote operation and high sensitivity for surface flaws. However, non-uniform electromagnetic properties [4] and surface roughness of the clad largely pollute eddy current signals, which in turn leads to detection errors. Namely, whether or not a defect is detected depends not only on the size of the defect but also on the noise in its vicinity, with different locations leading to different noise levels. Deterministically evaluating the results of the inspection based on a large safety factor would lead to an unnecessary burden or improper assignment of resources. Consequently, there is a need to probabilistically quantify the detection capability of ECT.

The probability of detection (POD) is a typical concept to probabilistically evaluate the detection capability [5,6]. However, analyzing the above-mentioned problem using the conventional POD model (developed in the US aerospace industry[5,6]) leads underestimating detectability[7]. The two most plausible reasons for this are described as follows. First, conventional POD uses a single parameter to characterize a defect, whereas at least two parameters, diameter and depth, need to be considered to analyze eddy current signals due to corrosion[8]. Second, conventional POD focuses only on the signal amplitude, while ECT signals are defined by two signal features, amplitude and phase. In order to investigate the capability of ECT to detect signals due to flaws and in the presence of high noise levels which are typical in the inspection of corrosion on stainless steel welds, it is necessary to develop a more accurate POD model.

In this context, the present study proposes a POD model that considers multiple flaw parameters and multiple signal features. Welded plate samples were prepared to simulate the inner surface of a pressure

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vessel. Then, eddy current testing was performed to collect signals due to drill holes that were machined into the samples to simulate corrosion. Signals analysis using the proposed POD model demonstrates a more accurate evaluation of ECT detection capability compared to a conventional approach.

2. Eddy current examination of simulated pits in austenitic stainless steel welds

2.1. Sample preparation

Figure 1 illustrates a welded plate sample that was prepared for this study. Samples are steel plates, either SM490 or ASTM A387 Gr22, cladded by an austenitic stainless steel-based welding metal, US-B309L, commonly used on the inner surface of pressure vessels to protect from corrosion. The cladding was done by electro slag welding and had a thickness of approximately 5 mm; the width of a weld bead was 50-60 mm. For this study, 10 welded plate samples with different dimensions (as illustrated in Figure 1) were prepared; the number of weld beads a sample contains ranges from 4 to 6 depending on the dimension of the sample. The surface of the cladding was ground after welding so that its roughness, R_z (JIS2001), was approximately 4.7 – 5.6 μm. A ferrite content measurement scope (Ferrite scope FMP30, Fischer Instruments K.K, Tokyo, Japan) revealed that the ferrite contents of the cladding ranged from 4 to 8%.

In order to simulate corrosion pits, 159 drill holes were machined 30 mm apart, along the center and in the middle of neighboring bead lines, as shown in Figure 2. The values of the various drill holes' diameters and depths were summarized in Table 1.

2.2. ECT inspection

Signals were collected using a commercial ECT instrument (aect-2000N, Aswan ECT Co., Ltd, Osaka, Japan) and a differential type plus point probe [8] illustrated in Figure 3. The exciting frequency was 100 kHz, and the probe was positioned in such a way that its coils and the weld bead line made 45 degree angle in order to reduce noise.

An XY stage was utilized to move the probe to scan samples at a constant speed. Signals were collected at grid points with pitches of 1 and 0.5 mm, parallel and perpendicular to the weld bead lines, respectively. The lift off, which is the distance between the bottom surface of the probe and the highest surface of the sample in the scanning area, was set to 1.0 mm. Signals were normalized so that the maximum signal due to an artificial slit whose length, depth and width are 20, 5, 0.5-0.6 mm, respectively, on an Inconel600 plate became 1.0 V and 0 degree.

Throughout this study, defect signals are defined as signals having their maximum amplitude contained in a 10×10 mm square area surrounding a drill hole. Noise was extracted in a similar manner, with the remark that centers of the square areas used for extracting noise encompassed all the points on the defect-free samples.

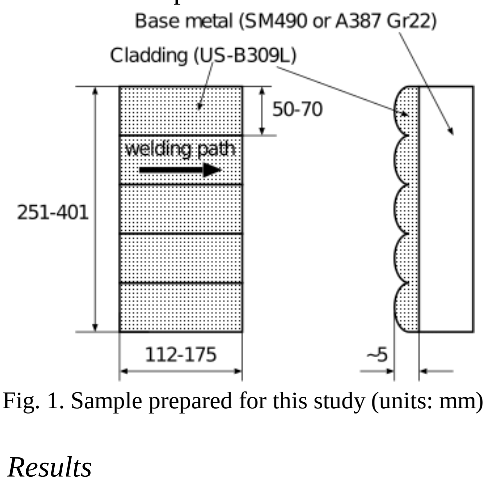


Fig. 1. Sample prepared for this study (units: mm)

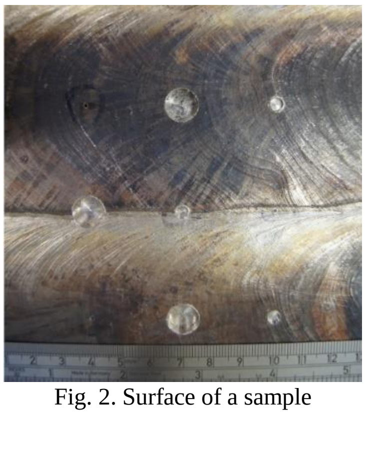


Fig. 2. Surface of a sample

2.3. Results

Frames (a)-(f) in Figure 4 show how the amplitude of the signal changes with the depth and diameter of the drill hole. The data indicate that it is not reasonable to evaluate the POD using a single defect parameter, namely either the depth or diameter, because the effect of depth on the amplitude depends on the diameter, thus considering both is necessary.

Figure 5 compares the noise and signals due to drill holes of a certain diameter and depth on an impedance plane. Noise is generally distributed in the third and fourth quadrants. The radius of each circle in the figure corresponds to the maximum amplitude of the noise. Some of the defect signals are inside the circle but do not overlap the noise. This indicates that using only the amplitudes of the measured signals leads to an underestimated POD; thus, evaluating signals on an impedance plane is necessary for a proper evaluation of the POD.

Table 1
The number of drill holes introduced into the samples

diameter \ depth	0.3	0.5	1.0	3.0	4.0	7.0
0.5	4	4	4			
1.0	4	3	19	9	15	8
3.0			9	9	9	
4.0			6		6	8
5.0			9	9		
10.0			8		8	8

(unit: mm)

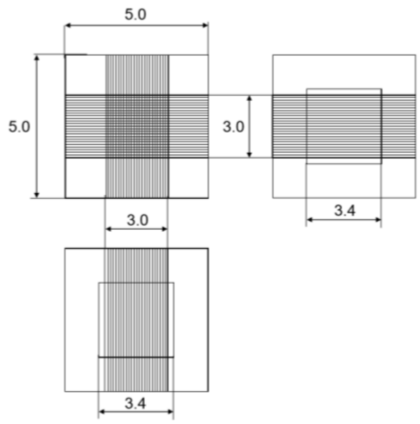
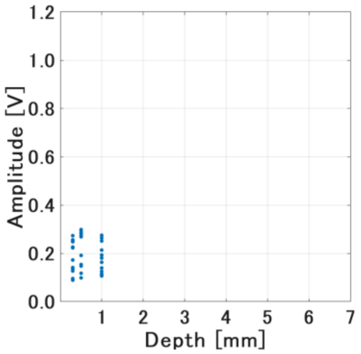
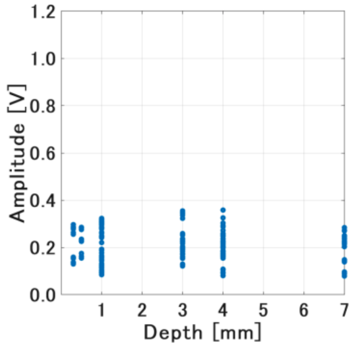


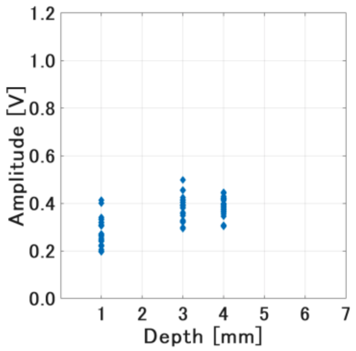
Fig. 3. Plus point probe (unit: mm)



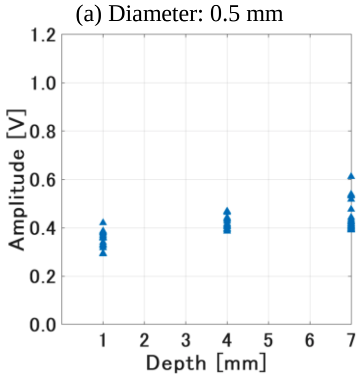
(a) Diameter: 0.5 mm



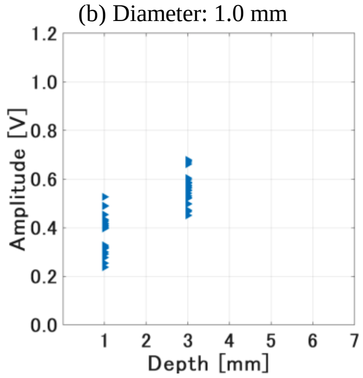
(b) Diameter: 1.0 mm



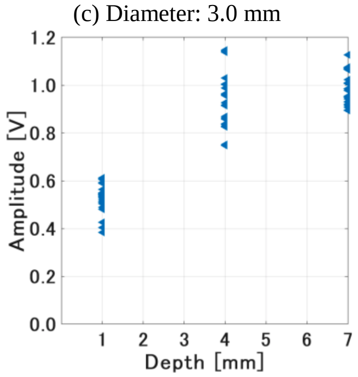
(c) Diameter: 3.0 mm



(d) Diameter: 4.0 mm



(e) Diameter: 5.0 mm



(f) Diameter: 10.0 mm

Fig. 4. Amplitudes of the measured ECT signals

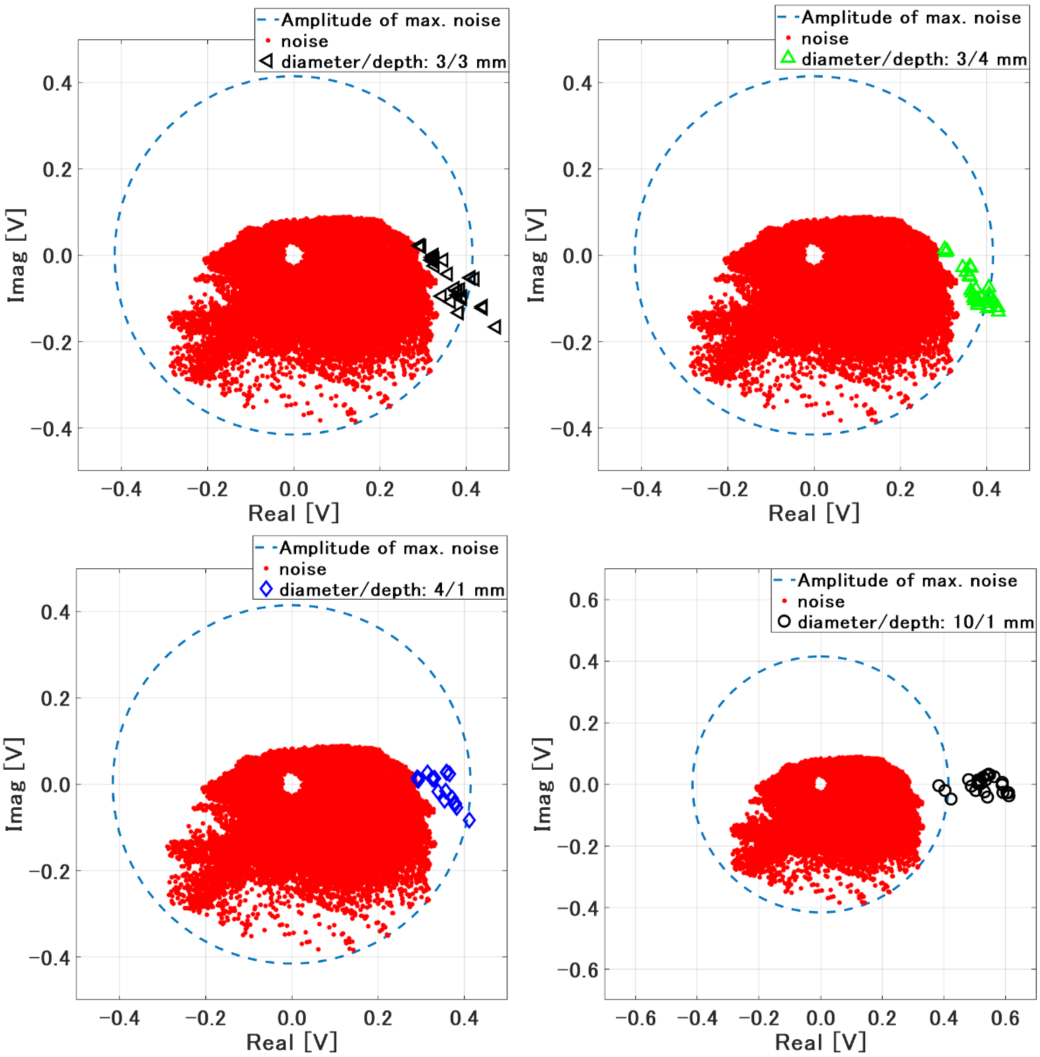


Fig. 5. Noise and signals due to drill holes

3. POD analysis

3.1. Multi-parameter POD using multiple signal features

There are two basic approaches to calculate the POD: *â-a* and hit/miss models. Whereas the former, *â-a*, is more general, it requires to correlate the flaw parameter, *a*, with the signal due to the flaw, *â* [10-13]. Obtaining a closed-form expression of the correlation is difficult because signals due to flaws with the same diameter and depth are significantly different from each other as shown in Figure 5. Thus, this study proposes a multi-parameter POD model that considers multiple flaw parameters and signal features based on the hit/miss approach.

The basic concept of the hit/miss approach is relatively simple. First, a decision threshold, which defines “a flaw is detected”, is chosen. The simplest criterion for this is whether or not the amplitude of a measured signal exceeds a certain value. Second, the ratio of the number of detected to undetected flaws is evaluated as a function of flaw parameters. Then the ratio is approximated analytically as a function of the flaw parameters.

In this study two decision thresholds are considered: the circle and the noise boundaries as depicted in Figure 5. More specifically, it is assumed that a flaw is detected when its signal is outside either the circle or the noise areas, and is missed otherwise. In order to identify the boundaries of the area occupied by noise, the impedance plane was divided into squares of 0.005 V length, where a square containing noise is then element of noise area. Moreover, noise-free squares neighboring more than five noise elements were also included in the noise area. Figure 6 shows the noise areas identified by this algorithm, along with the circle. It should be noted that these two decision thresholds correspond to accounting for multiple (amplitude and phase) and single (amplitude) signal feature(s), respectively.

The analytical formulation that this study adopted to relate the POD to the defect parameters is an expanded log-odds model [5], given by:

$$\mathrm{POD}(x,y)=\frac{\exp(a+bx)}{1+\exp(a+bx)}\times\frac{\exp(c+dy)}{1+\exp(c+dy)}, \tag{1}$$

where *x* and *y* are the diameter and depth of a drill hole, respectively. The four coefficients (a, b, c, and d) were estimated from the calculated ratios using the least squared method.

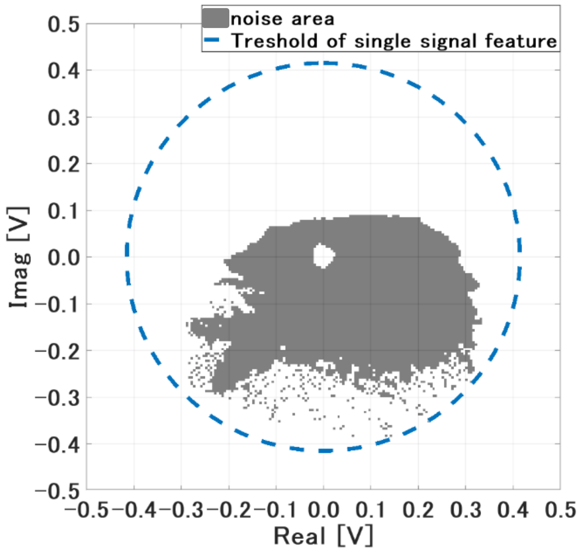


Fig. 6. The two decision thresholds: the circle whose radius is the maximum amplitude of noise and the noise boundaries

3.2. Results

Tables 2 and 3 summarize the ratios of “detected” drill holes evaluated using single and multiple signal features, respectively. The contour lines of the POD, obtained by fitting Eq. (1) to the ratios shown in the tables, are illustrated in Figures 7 and 8. The POD generated by the conventional method reveals that some drill holes have almost no probability to be detected regardless of their diameters, which obviously differs from the distribution of the original signals presented in Figure 5. Thus, considering only a single signal feature is not suitable for quantifying the detection capability of ECT. By comparison, the POD contour that includes two signal features more reasonably represents the detectability.

Table 2

The ratio of detected drill holes using single signal feature: amplitude (unit: mm)

Depth / Diameter	0.3	0.5	1.0	3.0	4.0	7.0
0.5	0.00	0.00	0.00			
1.0	0.00	0.00	0.00	0.00	0.00	0.00
3.0			0.00	0.15	0.30	
4.0			0.06		0.50	0.58
5.0			0.33	1.00		
10.0			0.92		1.00	1.00

Table 3

The ratio of detected drill holes using multiple signal features: amplitude and phase (unit: mm)

Depth / Diameter	0.3	0.5	1.0	3.0	4.0	7.0
0.5	0.00	0.17	0.00			
1.0	0.00	0.00	0.00	0.04	0.02	0.00
3.0			0.41	1.00	1.00	
4.0			1.00		1.00	1.00
5.0			0.85	1.00		
10.0			1.00		1.00	1.00

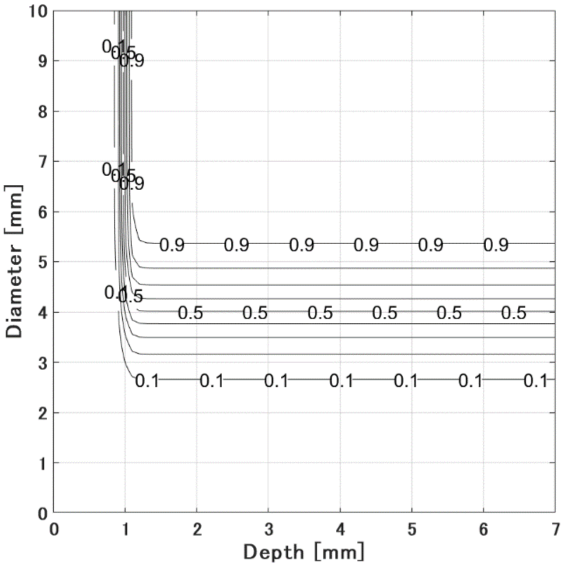


Fig. 7. Multi-parameter POD using single signal feature: amplitude

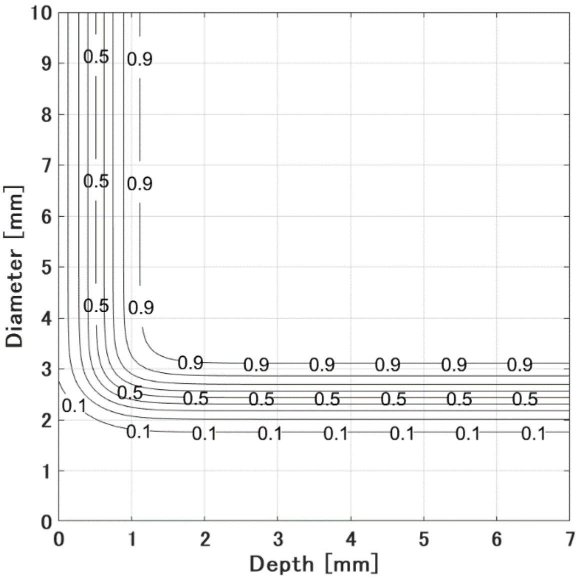


Fig. 8. Multi-parameter POD using multiple signal features: amplitude and phase

4. Conclusion

This study proposed a POD model using multiple signal features and multiple flaw parameters. Experimental evidence was provided to demonstrate its applicability to probabilistically evaluate ECT detectability of pits in stainless steel clad that simulated the inner surface of a large pressure vessel. Based on a conventional hit/miss model and considering multiple signal features and multiple flaw parameters, the proposed framework was able to separate signal from noise more reasonably than conventional single signal feature and single flaw parameter models.

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Thank you for your excellent contribution, and we look forward to receiving further submissions from you in the future.

Sincerely,

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