Analysis of Reliability and Effectiveness of Repeated Inspections Based on Probability of Detection Method

SEONHWA JUNG, YOUNGCHAN KIM and DOOYOUL LEE

ABSTRACT

Structural health monitoring (SHM) performs the function of evaluating performance and durability for structural life management by monitoring changes in engineering structures such as buildings and bridges. In order to obtain information about a structure's ability to perform its intended function, data collection activities are required through various inspections aimed at detecting the presence of structural damage. Repeated inspections have been proposed to increase the reliability of SHM. Many people considered repeated inspection as a way to increase the chance of detecting damage. If more than one of the individual inspections finds damage, collectively evaluates the damage as detected and produces the results of repeated inspections. Probability of detection (POD) was used as a measure of the sensitivity and reliability of the inspection process. To evaluate structural condition and predict remaining service life, POD is measured and structural life is calculated based on initial defect sizes that are just below the inspection limits of non-destructive testing techniques. Repeated inspections can be considered by multiplying the likelihood function, but if a single inspector performs repeated inspections, they may not be independent because they may be biased by previous inspection results. The repeated inspections is independent if performed by an automated system or another inspector unaware of previous inspection results. It can be assumed that each inspection is independent in that the SHM system can automatically collect data even in areas where general non-destructive testing is impractical due to complex geometries and accessibility limitations, but conversely, due to the dependencies of the data, there is no statistical difference between subsequent measurements. It is also considered to be less independent. In this paper, the effect of repeated inspection on POD improvement was confirmed using eddy current inspection data, and the benefits of repeated inspection differed from those predicted by assuming complete independence. Furthermore, the effectiveness of repeated inspection was discussed.

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INTRODUCTION

Reliability is an important aspect of structural health monitoring (SHM) because it helps to ensure that the system works as intended and that the data collected is accurate and reliable [1]. There are several ways to achieve reliability in structural health monitoring systems. First, various physical sensing and measurement techniques are combined with continuous remote processing to capture, record, and continuously analyze realtime data. Second, use wireless smart sensors and sensor network technologies to build a monitoring system that is more efficient and economical than traditional wired monitoring systems [2]. Third, proper verification and validation (V&V) should be conducted that explicitly evaluates all aspects of the SHM system that may affect its ability to detect, localize, or characterize damage [3]. Finally, repeated inspections can reduce measurement error and increase the likelihood of detecting damage to the structure. Repeated inspections can help extend the useful life of a structure by identifying problems early and allowing for timely repairs before more serious structural defects occur [4].

Nondestructive testing (NDT) is used as an integral part of SHM to gather information on parameters related to structural performance, including displacement, strain, and stress. This information is combined with postprocessing tools to infer the current operating condition and remaining life of the structure [5]. Several NDT methods are currently used in SHM systems, including radiography, ultrasonography, magnetic testing, and eddy current inspection. Kot et al [5] critically reviewed recent research advances, focusing on NDT techniques for SHM, presenting sensing methods, their operating principles, and installation techniques.

Probability of detection (POD) is a method of determining the ability to detect defects and is used as a measure of the reliability of NDT systems [6]. In this paper, eddy current inspection data were used to determine the impact of repeated inspections on improving POD and to determine if the benefits of repeated inspections differ from those predicted by assuming complete independence. Furthermore, the effectiveness of repeated inspection is discussed.

MODEL FOR REPEATED INSPECTIONS

Independence of Repeated Eddy Current Inspections

Eddy current inspection is a non-destructive testing technique used to detect surface and subsurface defects in conductive materials. Repeated eddy current inspections by multiple inspectors can increase the probability of detection. Repeated inspections by multiple inspectors are expected to increase the probability of detecting defects by reducing measurement error and ensuring accurate signal analysis. Traditionally, many have assumed that repeated inspections are statistically independent events that increase the likelihood of finding defects and improve POD. However, previous studies have described the error in assuming independence of repeated inspections and demonstrated that there is very little independence between inspections [7]. Forsyth [8] recommended against using the assumption of statistical independence when applied to repeated non-destructive testing.

POD of Repeated Inspections

Repeated inspections can be considered by multiplying the likelihood function, which may not be independent if performed by a single inspector because they may be biased by the results of previous inspections. They are independent if performed by an automated system or by another inspector who is unaware of the previous inspection results. Assuming that the repeated inspections are perfectly independent, the POD obtained after n inspections is as follows [9].

$$POD(a) = 1 - \prod_{\mathrm{i}=1}^{\mathrm{n}} \left(1 - POD_i(a)\right), \forall a > 0 \tag{1}$$

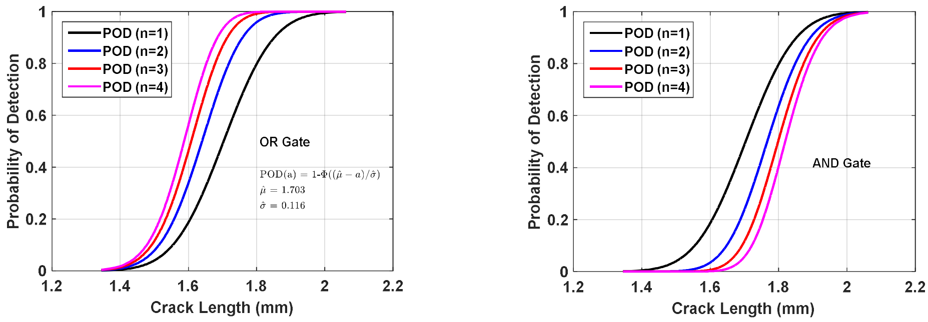
where n is the number of inspection repetitions and $POD_i(a)$ is the POD for the defect size a of the i-th independent inspection. According to Eq. (1), it is expected that as the number of repetitions increases, the POD obtained from repeated inspections improves and the probability of finding a defect increases. This is because if at least one of the individual inspections finds a defect, they are collectively evaluated as having detected the defect and generate the result of the repeated inspection. Eq. (1) is a quantitative analysis of an OR gate among logic gates. An OR gate returns true as the output when at least one of the inputs is true, and false as the output when all the inputs are false.

If all individual inspections must find a defect to collectively evaluate as a defect detected, the POD obtained after n inspections can be expressed as Eq. (2).

$$POD(a) = \prod_{i=1}^{n} POD_i(a), \forall a > 0 \tag{2}$$

Eq. (2) is equivalent to a quantitative analysis of an AND gate among logic gates. An AND gate returns true as its output if all of its inputs are true, and false as its output if at least one of its inputs is false. If we use Eq. (2), it is expected that as the number of repetitions increases, the POD obtained by repeated inspection will degenerate and the probability of finding a defect will decrease. In fact, if at least one of the individual inspections finds a defect in the repetition, the defect is considered to be detected in the aggregate, so it is reasonable to apply the logic of the OR gate to check the effectiveness of the repetition.

Figure 1 illustrates the OR gate model and AND gate model. Applying the OR gate model, Figure 1(a), the mean of the POD curve decreased as n increased. This can be expressed as an improvement in POD, which means that as n increases, the defects are better detected. On the other hand, when the AND gate model is applied (Figure 1(b)), as n increases, the mean of the POD curve shifted to the right. For example, in Figure 2(a), we can see that the probability of detection increases as n increases when the defect size is 1.8 mm. But in Figure 2(b), we can see that the probability of detection decreases as n increases when the defect size is 1.8 mm. In both cases, as the number of repetitions increased, the variance of the POD curve decreases as the number of repetitions increases. If we apply the logic of the OR gate to the repetitions, theoretically, as the number of repetitions increases the POD is expected to improve as shown in Figure 1(a).



(a) (b)

Figure 1. Effect of inspection on POD when repeated inspections are completely independent (a) OR gate model (b) AND gate model

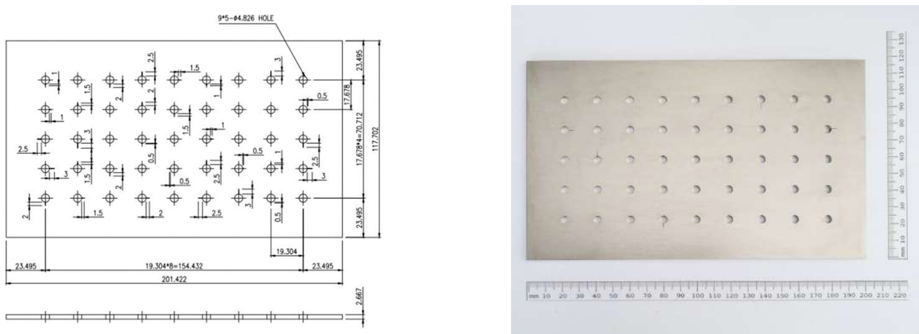
EXPERIMENTAL

Materials

The material for the experiment was Ti-6Al-4V. The mechanical properties of Ti-6Al-4V can be found in Table I. Forty-five holes were created in a Ti-6Al-4V plate as shown in Figure 2, and artificial defects of different sizes were created by electrical discharge machining (EDM) in 30 holes, while the remaining 15 holes were utilized as defect-free controls. The overall dimensions of the specimen are 201.422 mm (W) × 117.702 mm (D) × 2.667 mm (H). The sizes of the artificial defects were 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 mm, with five of each size for a total of 30 defects.

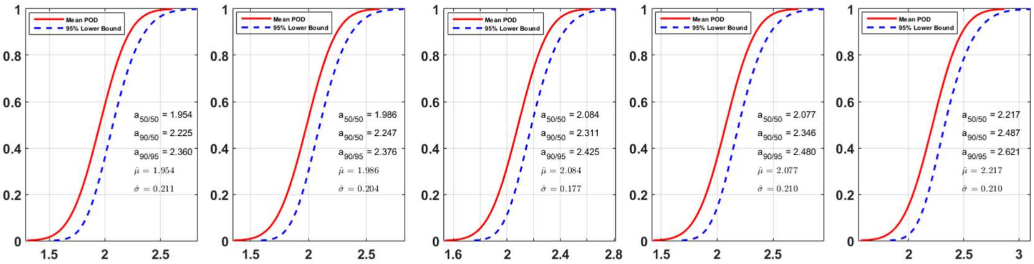
TABLE I. MECHANICAL PROPERTIES OF Ti-6Al-4V [10]

Properties	Values
Tensile strength (MPa)	950
Yield strength (MPa)	880
Elastic modulus (GPa)	113.8
Poisson's ratio	0.342



(a) (b)

Figure 2. (a) Blueprint of specimen and (b) front side of specimen



(a) (b) (c) (d) (e)

Figure 3. Individual inspections POD curves. In each plot, the horizontal axis is the crack length (mm), and the vertical axis is the probability of detection. The red solid line is the mean POD and the blue dotted line is the 95% confidence interval. (a) to (e) Inspection results conducted by inspectors 1 to 5

Eddy Current Inspection

In eddy current inspection, a probe is placed on the surface of the part and electronic equipment monitors the eddy currents in the workpiece through the same probe [11]. When a differential coil probe is used to inspect a defective tube, the impedance of the inspection coil is changed and the defect signal is extracted and output by a quadrature amplitude demodulator [12]. The acquired signal is displayed from 0% to 100% intensity.

To determine the effect of repeated inspection on the probability of detection, five inspectors performed eddy current inspections. Eddy current signals were generated with a NORTEC 600D.

RESULT AND DISCUSSION

POD of Individual Inspection

The POD curves for each of the five inspectors are shown in Figure 3. The noise level was set to 10% and the decision threshold to 30% according to the US Air Force Technical Manual [13].

POD of Repeated Inspection

Pairing 5 inspectors with 2 inspectors yields a total of 10 combinations. Combine the data from the inspections performed by the two inspectors to create a combined POD curve and see what changed from the individual inspections. Figure 4(a) shows an example POD with combined data for one of the 10 pairs of combinations. The gap between the mean line (solid line) and the 95% confidence lower bound (dashed line) indicates how much uncertainty there is in the inspection results, and you can see that the uncertainty is lower for the combined data than for the individual inspections. This indicates more reliable results in determining the likelihood of detecting a defect.

Next, we applied the OR gate model and AND gate model for the inspection results of the two inspections. Figure 5 shows the combined POD results generated by combining the data applying the OR gate model or AND gate model.

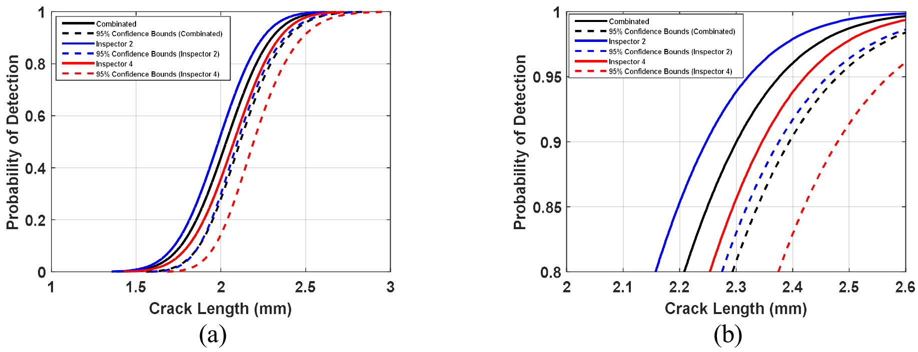


Figure 4. (a) POD curves generated by combining the results of 2 inspections showing combination of the results of inspectors 2 and 4 (b) Zoomed-in view

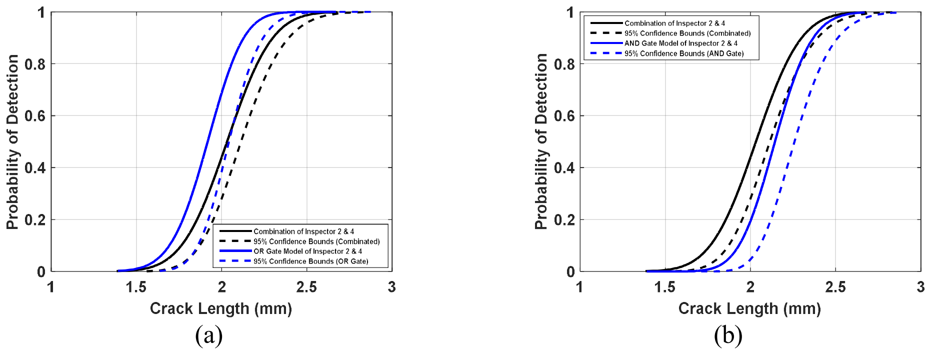


Figure 5. POD curves generated by combining the inspection results of inspectors 2 and 4 applying (a) the OR gate model and (b) AND gate model

From Figure 5(a), it can be seen that the combined POD curve generated by combining the data from both inspectors is to the right of the POD curve generated by applying the OR gate model, and the two curves do not show the same results. The opposite result was obtained when the AND gate model was applied.

Discussion

In general, the estimate of a_{90} is defined as the size POD(a_{90}) = 0.90, and defines a defect size for a 90% POD at a 95% confidence level as $a_{90/95}$ as the detectable defect size. The defect size $a_{90/95}$ is an accepted measure of the minimum defect size that can be reliably detected by non-destructive testing and is the detection limit [14-15].

In Figures 6, we show the distributions of $a_{90/95}$ of the results of applying the individual inspection, the data combined result of the two inspectors, the OR gate model and the AND gate model. Figure 6(b) plots the 10 $a_{90/95}$ on a normally distributed probability map, the estimated value of $a_{90/95}$ at the 95% confidence level is 2.606 mm, which is similar to the distribution of individual inspections $a_{90/95}$ distribution in Figure 6(a). The standard deviation was the largest for the $a_{90/95}$ distribution of individual inspections, and one of the individual inspection $a_{90/95}$ values was outside the 95% confidence level.

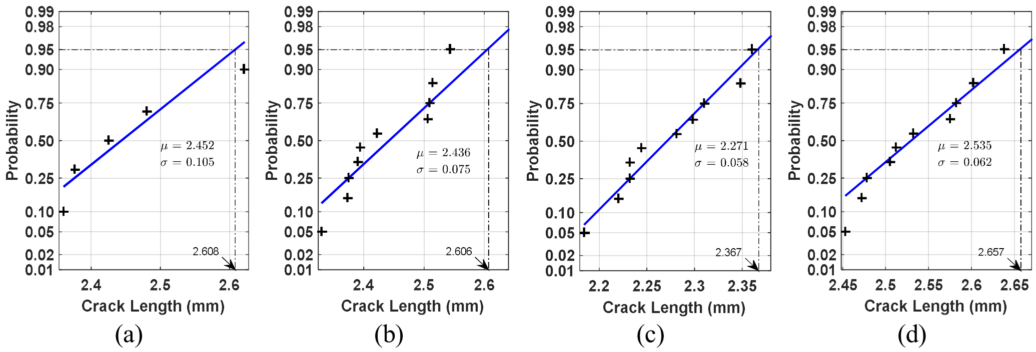


Figure 6. Normal distribution probability plot of $a_{90/95}$ of (a) individual inspections, (b) repeated inspections , (c) applying the OR gate model and (d) applying the AND gate model

Figure 6(c) and (d) show the theoretical results of the different logic of defect detection when repeated inspections are assumed to be completely independent. When applying the OR gate model the mean value of $a_{90/95}$ and the value estimated at 95% confidence level of $a_{90/95}$ were smaller than the results of individual inspections or the combined data of the two inspectors. Conversely, when the AND gate model was applied, both values were larger than the individual inspections or the combined data from two inspectors. Regardless of how the logic is applied, the conclusion is that the data from the two inspectors are not completely independent when combined.

While the results were similar to the OR gate model in the sense that the POD improved as a result of the repeated inspections, the results were not exactly the same in that the repeated inspections were not completely independent. To ensure the independence of repeated inspections, additional efforts are required, such as having inspectors who are unaware of the previous inspection results, using different inspection equipment or establishing defect detection data by automated sensors to eliminate human intervention. In addition, the OR gate model was limited in its ability to reproduce the repeatability of the a vs â method, which uses a continuous signal amplitude based on crack size. It is necessary to improve the OR gate model presented in this article to fully reproduce the repeatability of the a vs â method.

On the question of whether repeated inspections are independent, the study did not produce the same results as the theoretical probability of detection if they were perfectly independent, but it did demonstrate that they are beneficial to defect detection in that they reduce the uncertainty of the inspection results. Repeated inspections are recommended because they reduce measurement error and increase reliability in detecting structural damage.

CONCLUSION

Artificial defects were created by electrical discharge machining on Ti-6Al-4V, and the signal to the defect was measured by eddy current inspection. The effectiveness of repeat inspections was analyzed based on inspections performed by five different inspectors on the same specimen. The results showed that repeat inspections did not dramatically improve POD, but they did help to reduce uncertainty, making the inspections more reliable. The data for the repeat inspections was generated by aggregating the data from the individual inspections. The experimental results differed from the POD curve that would be expected if the repeated inspections were completely independent, and it was concluded that the inspections were not completely independent. The proposed OR gate logic was limited in its ability to fully reproduce repeated inspection for continuous signals in the a vs â method. Additional measures were proposed to make the logic of the iterative inspection more rigorous, such as deriving a modified logic expression, further refining the defect size, and referring the inspection to a completely different organization.

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