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A Model Assisted Probability of Detection Approach for ECNDT of Hidden Defect in Aircraft Structures

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Abstract—In a probabilistic approach, the performance of the control is characterized by statistical indicators such as the Probability of Detection (PoD) which describes the probability of detecting a defect of a given size knowing that it is present in the inspected structure. In this paper, an experimental analysis and simulation using FEM of the eddy current testing on three-dimensional riveted structure is performed on small fatigue cracks to identify and quantify probability of detection curves. The PoD curves are plotted in terms of characteristic dimensions of the defect (depth, length, orientation, etc.) and are dependent on a number of factors including material, geometry, defect type, operator, and environmental effects.

1. INTRODUCTION

The choice of control technique is the result of a compromise among the desired detection sensitivity, the accessibility of the area to be controlled, the ecological impact of the inspection method, and the cost of implementation during equipment maintenance operations [1]. The two most frequent degradations are fatigue and corrosion [2]. One of the major challenges is to monitor the rivet lines to detect possible cracking phenomena that can be created at the rivet base, Figure 1, and propagate due to the high mechanical stresses that are exerted on them [2]. Indeed, the cracks present in riveted structures originate at the rivet base and grow along the axis of the rivet line [3].

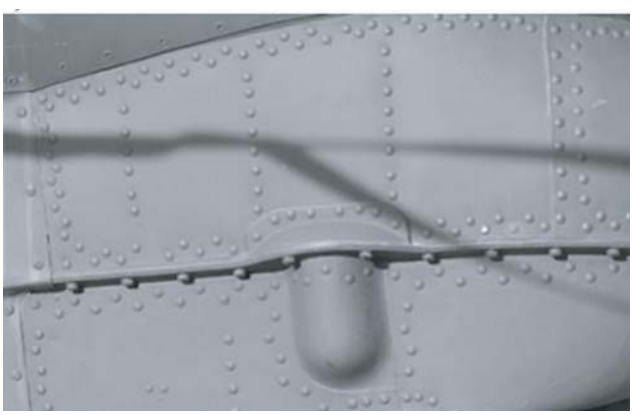

Figure 1. Riveted joints in aviation structure.

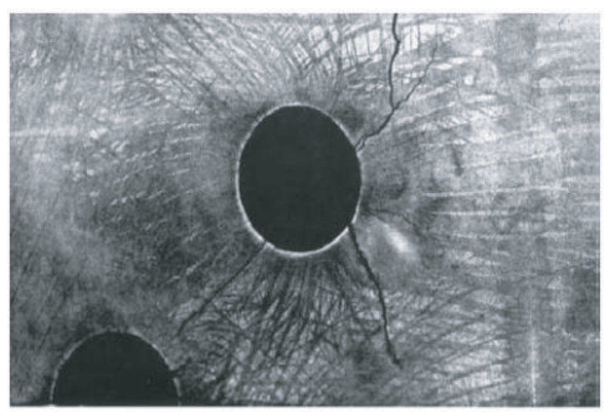

Figure 2. Damaged rivet hole.

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The detection of these defects must be carried out early before the rivet propagates from rivet to rivet, Figure 2, which could cause the fuselage to tear off during flight [4]. These maintenance operations are costly (aircraft downtime) and essential for passenger safety, which explains the importance of optimizing inspection procedures. The use of simulation tools is a valuable aid in the development of control methods, their optimization, and qualification [3].

2. NDT MODELLING AND POD CURVE GENERATION

The nondestructive evaluation techniques used for the qualification, inspection, and safety of riveted structures in the aeronautical sector are required to meet very high standards of reliability and, consequently, to provide a much higher level of performance for improved detection capability [5–7]. An approach based on the estimation of the probability of detection has become an indispensable tool for researchers for a good evaluation of the used nondestructive testing techniques performances. The evaluation of reliability in nondestructive testing will necessarily involve the evaluation of the technical performance taking into account variability such as human and environmental factors [8–11]. The work presented in this paper aims to investigate the feasibility of using the finite element (FE) simulations to generate PoD curves for eddy current inspection using a 3D riveted structure containing both surface and deep crack defects. The probability of detection curve assesses the capacity for crack detecting as a function of the crack length [12]. In a perfect case, an evaluation of the PoD would be zero if the defect signals were less than the established critical size. Otherwise, it would be equal to the unit for higher defect signals. Totally different defects can rise to similar eddy current signals [13]. For this, the multifrequency technique and pulsed eddy current technique will be used. In the first mode, a wide frequency band from 100 Hz to 10 MHz is used to take into account all the different depths of the tested defect. On the other hand, in the second mode, a pulse signal of a fairly well-known shape is used as the input of the excitation signal as a function of time. The PoD is written as a function defect size. One of the functions used in non-destructive inspection is now the cumulative log-normal distribution function. Researchers have adopted a technique for analyzing the response signal from any defect. Indeed, we use a measured value to establish a quantitative dependence with the actual size of the defect [14]. The mathematical relation between the measured value and the actual size of the crack defect can be expressed as:

$$\ln(a) = \beta_0 + \beta_1 \ln(\hat{a}) + \delta \tag{1}$$

where $\ln(\hat{a})$ represents the relative measured value of the signal response from the crack defect, whereas $\ln(a)$ indicates the relative value of the defect size. The unknown β_0 and β_1 are regression parameters, and δ is the error term normally distributed with constant standard deviation σ_δ [14]. These previous parameters are unknown and have to be estimated from experimental data [12]. In order to detect a defect, the response is analyzed, and a decision is taken: if the measured value $\hat{a}$ exceeds the predefined threshold value $\hat{a}_{th}$. The probability of detection can be calculated from the following expression:

$$PoD(a) = \text{Probability}(\ln(\hat{a}_{th}) > \ln(\hat{a})) \tag{2}$$

$$PoD(a) = 1 - \Phi\left[\frac{\ln(\hat{a}_{th}) - (\beta_0 + \beta_1 \ln(\hat{a}))}{\sigma_\delta}\right] = \Phi\left[\frac{\ln(\hat{a}) - \mu_m}{\sigma_s}\right] \tag{3}$$

where Φ is the cumulative distribution function of the standard normal distribution, and μ_m and σ_s represent the mean and standard deviation, respectively [15]. The design, development, and optimization of eddy current NDT processes are made possible by the numerical modeling of electromagnetic systems. Nevertheless, the reliability of the simulations depends on rigorous validation [10]. Simulation tools are therefore very useful for studying the influence of various parameters on the electromagnetic phenomena involved. The multifrequency and pulsed eddy current technique are governed by formulations derived from Maxwell's equations and the laws of material [16]. In this paper, a numerical approach based on the finite element method is used due to its flexibility and ability to handle complex structures [17]. It is more general, numerically superior, primarily used for its versatility modelling of material properties, simulations of boundary conditions, modelling arbitrary domain space, and substantially reduces the experimental work [18].

3. APPLICATION AND RESULTS

Before addressing the work on the estimation and evaluation of the probability of detection, we will devote this part to the modeling of a riveted structure by exploiting the results obtained from eddy current sensors in absolute mode. Several researchers have developed both analytical and numerical approaches in order to develop this direct model by calculating the necessary quantities including impedance calculation, reaming and alteration of the model by a defect [16, 19]. The proposed model had to be able to take into account the multilayer configuration of the riveted structure with a variation in the properties of each layer of the structure under test. The design configuration consists of a part made up of a stack of three aluminum plates with bores that can accommodate tapered at head rivets [20]. The upper and two lower plates, with a conductivity of 17 MS/m, are 2.5 mm and 4 mm thick, respectively. The head of the bores have a diameter of 12 mm and the body of 6.35 mm. The crack defect takes the form of a parallelepiped with a width and height of 5 mm and a depth of 0.2 mm as shown in Figure 3. Figure 4 shows an overview of the probe mesh, rivet, and crack defect. The total number of elements after refinement is more than one million second-order tetrahedral elements, and the estimated computation time corresponding to the 5 kHz is about 3 hours performed on a workstation with an Intel Core i7 @ 4.10 GHz processor and 6 GB RAM. The modeling results are obtained by using a commercial FEM platform Comsol Multiphysics 3.5a [21].

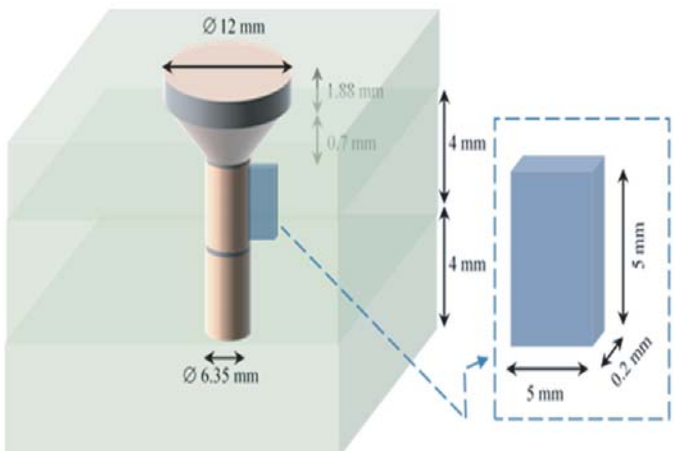

Figure 3. Subsurface crack in multilayer model.

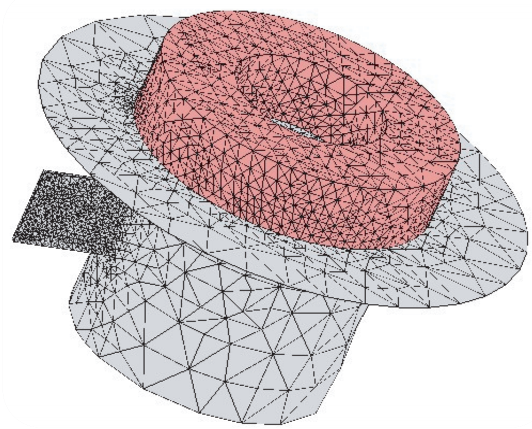

Figure 4. FEM Mesh.

The relative impedance variations due to the presence of cracking defects in the riveted structure are generally very small compared to the impedance values measured on a defect-free material [22]. In order to show them, it is necessary to perform a difference measurement, which also makes it possible to reject certain parameters effect. This difference can be made between a sensor and an identical sensor isolated from the reference target. When the positioning of the sensor is subject to variations, such a measurement could confuse a crack defect with a variation in parameters, such as a local variation of the lift-off varying between 1 mm and 2 mm as shown in Figure 5.

Figures 6 and 7 illustrate a comparison between finite element model and the experimental results of real and imaginary parts of impedance according to coil displacement, respectively. As expected, the results of the two models are close and sometimes even coincide with a few sensor displacements at 1.6 kHz. This can be justified by a simple calculation of the relative error between our simulated results and the experimental ones. This difference is rather acceptable since it varies between 0.12% and 6.81% for its maximum value. However, the contribution of the crack defect is slightly observed in absolute value on the imaginary part of the impedance. Symmetry concerning the zero displacements is also observed on the two results of the impedance components.

There is distinction between Figure 5 and Figure 8. The normalized impedance plan refers to a calculation of the two components of the normalized impedance and plotted against each other as

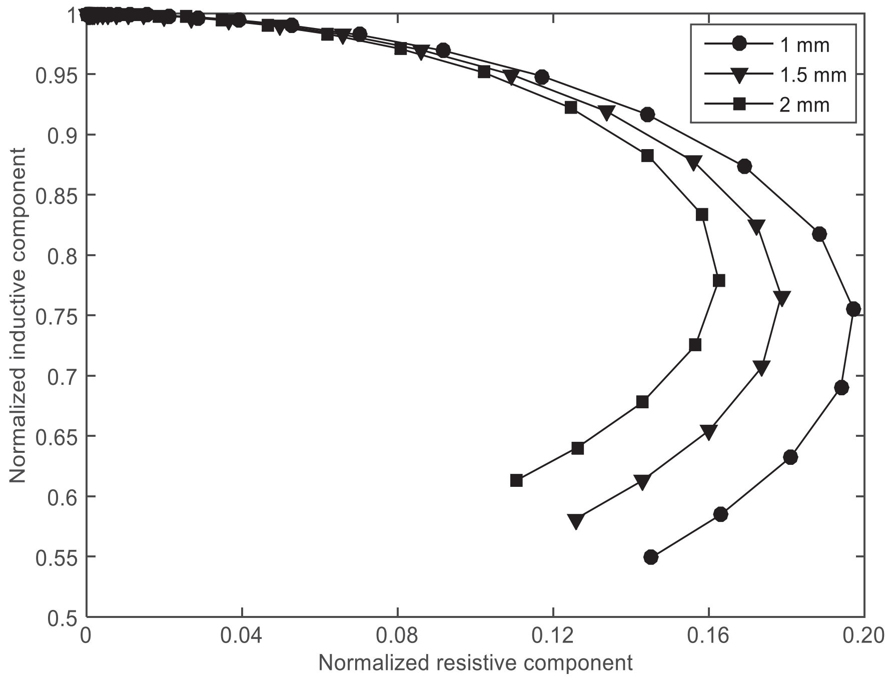

Figure 5. Effect of Lift-off distance on normalized impedance plane.

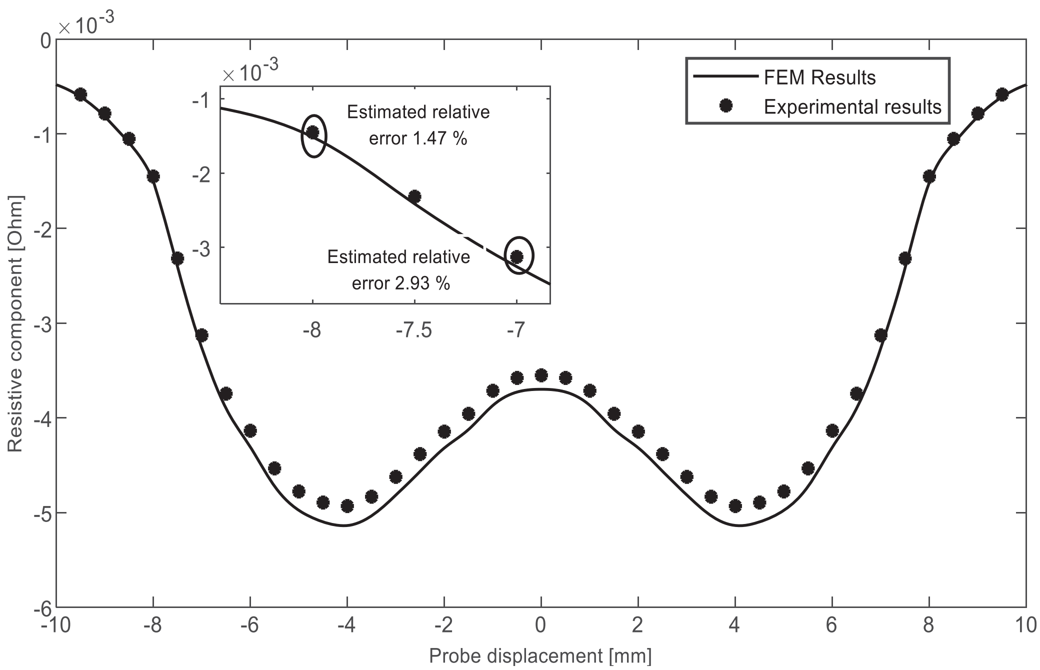

Figure 6. Variation of resistive component.

shown in Figure 5. The aim of the impedance normalization is to make the measurement independent of the characteristics of the exciter coil (number of windings, no-load losses). It depends only on the excitation frequency, the probe geometry, the probe/target distance (lift-off), and the parameters of the target, i.e., its geometry, electrical conductivity, and magnetic permeability. In figure 8, we plot the two components of the impedance (not the normalized impedance), and a comparison is made between the curves without and with the presence of a crack defect in the second layer.

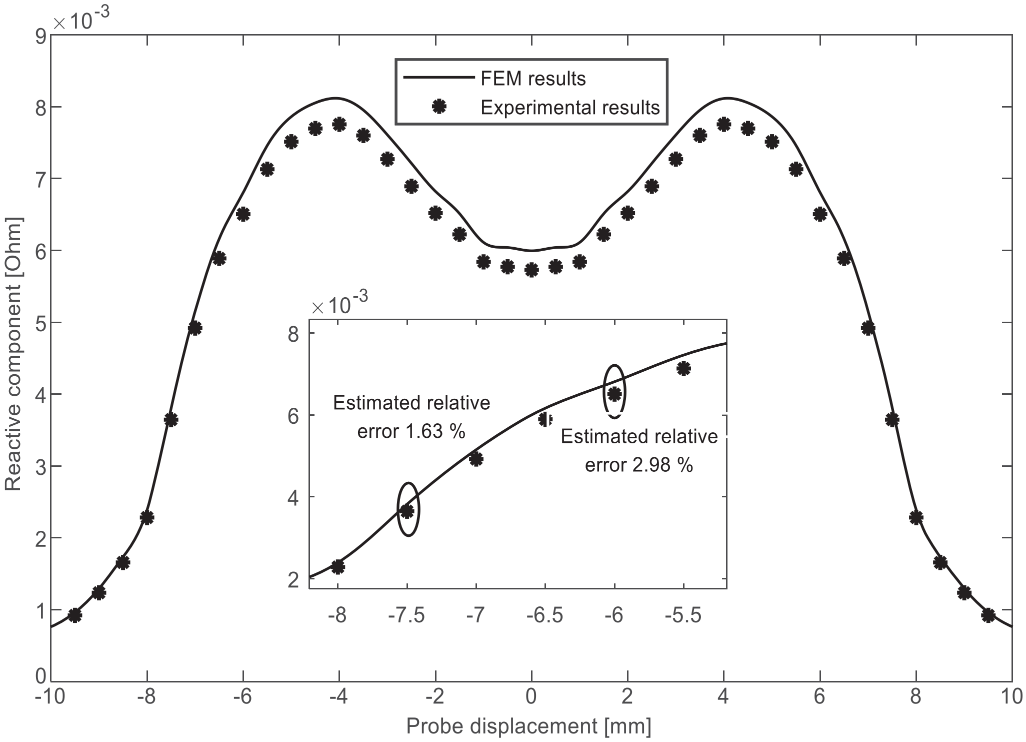

Figure 7. Variation of reactive component.

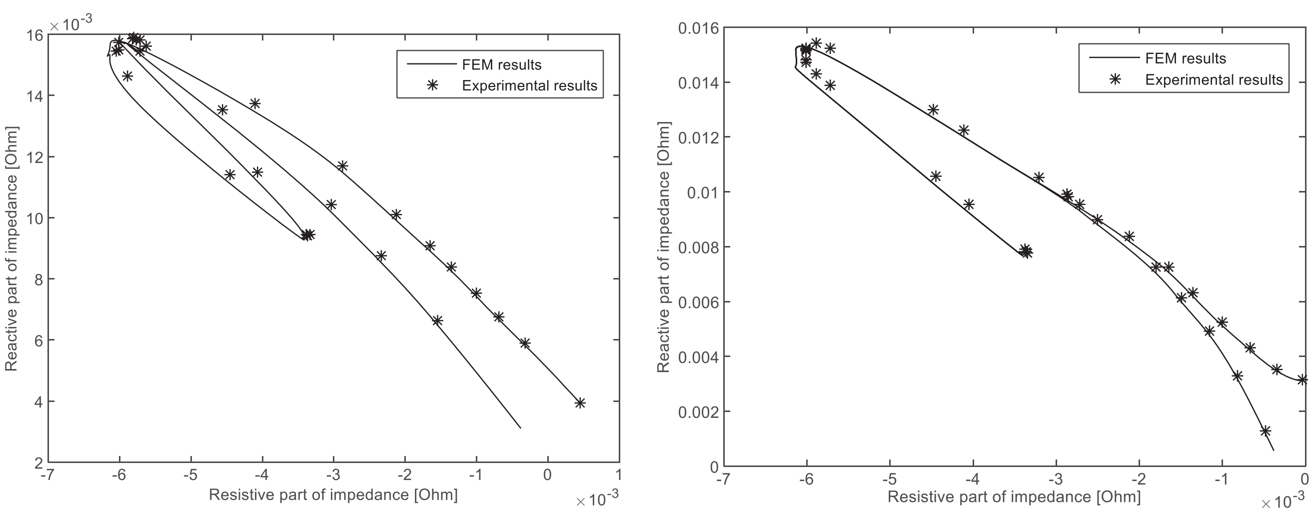

Figure 8. Effect of crack defect on impedance components. (a) Without crack defect. (b) With presence of crack defect on 2nd layer.

We note that the signals are not symmetrical during the first half of the probe course (for probe positions ranging from $x = -4$ mm to 0 mm), and the Lissajous curves of the crack signal have the same shape as those without crack defect. Then the signals with the disturbed defect are opened and centered in $x = 3$ mm. This opening of the signals is more obvious for a less embedded defect, such as our case where it is located in the second layer. The signal, resulting from the combination of deterministic and random phenomena, makes the probability of detection approach necessary to ensure good reliability

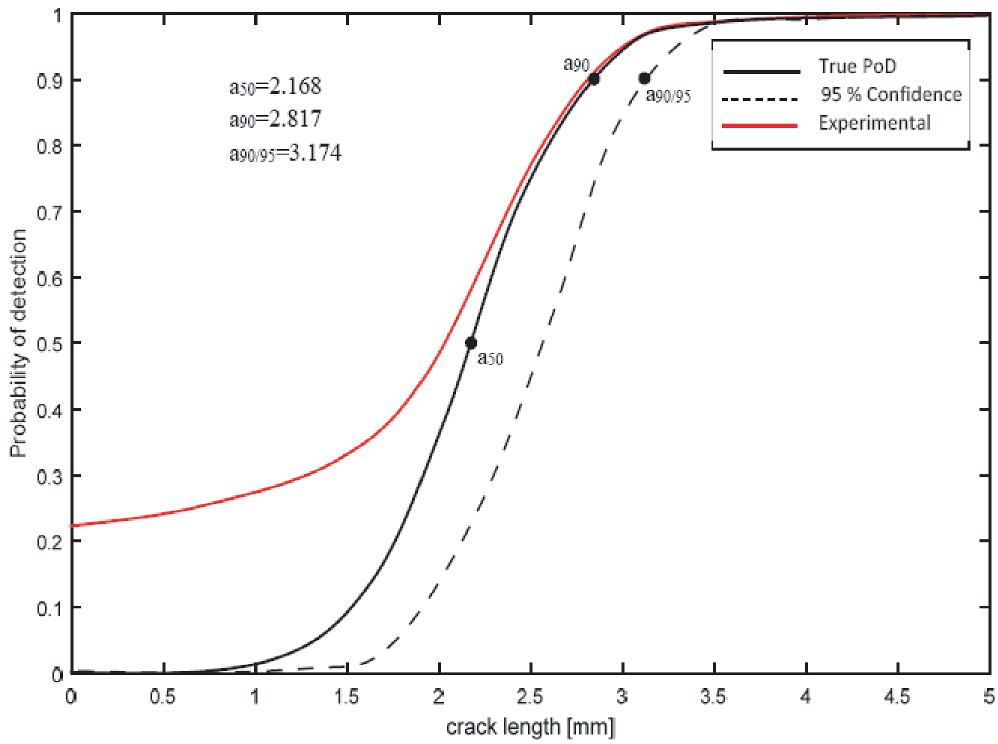

Figure 9. Experimental and estimation model of POD curve.

of the measurements taken and consequently decides about the detection performance of eddy current sensors. The first parameter is the characteristic quantity showing the evaluation of the probability of detection, and it will directly be related to the result that we will search: minimum value of the detectable defect (generally the length of the defect) [23]. The second parameter shows the uncertain values that define the proportionality between the length and depth of the crack. Figure 9 presents a comparison of the probabilities of detection results for the experimental and proposed models. We note here, on the one hand, the characteristic quantities which represent those against which the PoD is directly evaluated by looking for the minimum value of the detectable defect, and in most cases, we find the length of the defect. We remark that a good agreement between the PoD curve predicted by the EF simulation and that of the experiment can be observed in this figure

We remark that can be observed in this figure is the good agreement between the PoD curve predicted by the EF simulation and that of the experiment can be observed in this figure for faults deeper than 25% thus demonstrating the promise of simulations for the PoD characterization. For defects less than 25%, a shift between the two curves is observed.

4. CONCLUSION

This paper focuses on the statistical analysis for assessing the probability of detecting eddy current control in a riveted structure. We paid particular attention to comparing results from experimental and simulation data. Statistical analysis results were compared and explained. The parameters of the reliability assessment of the nondestructive testing including a_{50} (2.168 mm), a_{90} (2.817 mm), and $a_{90/95}$ (3.174 mm) were obtained. In addition, the PoD curve with lower bounds as a function of the defect length was drawn. The results obtained in this paper allow maintenance responsible to choose the most suitable nondestructive testing technique for better assurance and high detection reliability.

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