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Probability of Detection for Penetrant Testing in Industrial Environment

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Abstract

Introduced at the end of 60's by NASA, Probability of Detection (PoD) is becoming more and more one of the main approach in order to assess, quantitatively, the general detection capabilities of a Non Destructive Inspection process. In spite of its importance, PoD can be elaborated in a variety of ways and can lead to some misinterpretations. Alenia Aeronautica assessed a specific approach for *liquid penetrant inspection* that is strictly connected to the estimation of the inspection sensitivity and it can be aimed at various targets, such as: inspection procedure validation, evaluation of personnel proficiency, comparative analysis of penetrant inspection processing materials, equipment and procedures, and evaluation of automated inspection systems. To this purpose, PoD is conceived as the probability, at a fixed confidence level, to detect a discontinuity belonging to a predefined class. Experimental PoD curves are obtained by processing metallic samples with defects generated and developed under controlled conditions.

Keywords: `Probability of detection, liquid penetrant inspection.`

1. Introduction

The aim of this study is to evaluate the performance of non-destructive inspection (NDI in short) called Penetrant Testing (PT) used in the production of airplane parts and in many industrial applications where the detection of open defects is of interest. Liquid penetrants are used to locate surface-accessible defects in solid parts.

The Probability of Detection (PoD) concept, is strictly related to the one of reliability used within NDI, can be defined as follows: "The probability of finding a crack of given dimension, under precise conditions, by prescribed inspection procedures". Even more generally, a suitable definition of PoD is: "The probability of finding an anomaly of given characteristics, under precise conditions, using a specific inspection procedure".

The PoD concept was introduced by NASA [6]. Indeed, by 1969, the USA spatial agency started to develop a sequence of researches aiming to evaluate the reliability of NDI controls. These studies were used mainly within the development of space shuttle project and ended up with a huge number of experimental data and PoD plots. Since then, the concept of PoD has been further defined and specialized to various cases, becoming an usual method for definition of NDI process characteristics and performance. In general, PoD applications include methodologies: to establish acceptance criteria, to validate inspection procedures, to assess the performance of the inspectors, to compare more inspection techniques, to select/qualify inspection processes, to quantify inspection process sensitivity.

2. Liquid Penetrant Inspection

One of the criteria for the design of a critical component (as aeronautic structures) is the inspection-ability: the component is designed in such a way that his compliance with structural and functional requirements is verifiable through available and qualified non-destructive methods. This approach is applied to the military aircraft (fail-safe approach), and to the civil aircraft (damage tolerance approach). The fail-safe approach provides that the component is free from not acceptable defects, it is designed to remain intact for the whole planned life. The component is inspected after manufacturing and in case of accident. A damage tolerance design requires that a component affected by an anomaly is capable of sustaining the damage, provided it does not exceed a critical size and is revealed after manufacturing or during programmed inspections.

Of course, NDI have limits of detection and application: the diagnosed defects are dependent on various factors (intrinsic limitations of the applied physical principles, instrumentation adopted, accessibility and characteristics of the component, inspection procedure, human factors, etc.).

The problem of the inspection-ability requires to answer on three questions:

1. What types of defects are detectable?
2. What is the smallest detectable flaw?
3. What is the biggest flaw that may not be revealed?

The PoD is a way to answer those questions, especially the third.

3. General settings

There are essentially two methods for producing PoD curves (or the contrary, "acceptance curve", defined as 1-PoD):

- hit/miss (discrete data curve): an indication of anomaly can be detected, not detected, or doubtful;
- response curve (continuous data curve): the response to an indication of anomaly is dependent on an instrumental continuous parameter.

The method hit / miss [6] is applicable and sufficient for penetrant testing.

In any case, the methodology for obtaining PoD curves is based on the following steps:

1. definition of parameters for defect classification;
2. finding of samples and materials with representative defects;
3. inspection of the samples with a defined technics and procedure;
4. recording of results;
5. analysis and best-fit of results.

In case of data hit/miss, different distributions can be considered for the best-fit. The distribution of Fisk [2]

$$PoD(d) = \frac{e^{\frac{\pi}{\sqrt{(3)}}\left(\frac{\ln(d)-m}{\sigma}\right)}}{1 + e^{\frac{\pi}{\sqrt{(3)}}\left(\frac{\ln(d)-m}{\sigma}\right)}}, \tag{1}$$

where d, m and s are the size of the defect, the median and standard deviation, respectively, is often used. The Fisk (or log-logistic) is a typical continuous distribution for not negative random variables, often used in economics. These approaches have much limits because they are based on continuous quantities (size of the defect), that don't take into account other conditions that typically characterize an inspection.

In a Penetrant Testing the detection of an indication depends not only by its size, but also by its visibility, by the exposed volume of penetrating and by lighting conditions. For this reason, often (as with Alenia) ad hoc approaches are defined.

4. Alenia Aeronautics approach

Alenia Aeronautics approach is oriented to estimate the inspection process sensibility, by determining the PoD. To this end we provide the following definitions. Visibility level: the lowest value of the intensity of black light at which a discontinuity appears detectable by certified personnel. There are four levels of visibility L_v:

$$\mathbf{0} : L_v > 1\ \mathrm{W/m^2} \quad \mathbf{1} : 0.7\ \mathrm{W/m^2} < L_v \leq 1\ \mathrm{W/m^2}$$
$$\mathbf{2} : 0.4\ \mathrm{W/m^2} < L_v \leq 0.7\ \mathrm{W/m^2} \quad \mathbf{3} : Lv \leq 0.4\ \mathrm{W/m^2}\ . \tag{2}$$

Class of discontinuities: set of discontinuity whose indications have defined size and morphological characteristics and a given level of visibility.
PoD: for a defined inspection process, probability of detection of a discontinuity, with a defined level of confidence, depending on the class to which the discontinuity belongs. A PoD curve is given by PoD showing the dependency upon discontinuity classes.
DETEX (DETectability indeX): index of deceasing order of the detectability "difficulty". The different types of morphological defects are shown in figure 1. As far as the morphological types shown in figure 1 are concerned,

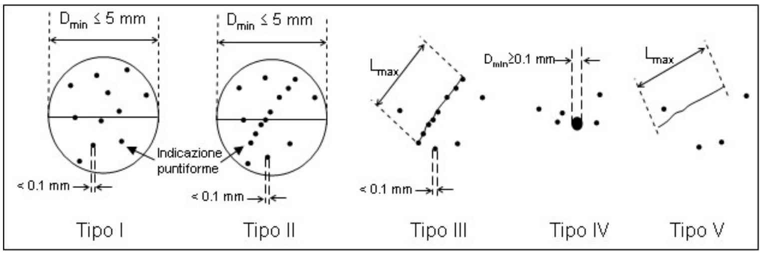

Fig. 1. Types of morphological defects.

the related DETEX indexes are defined as shown in table 1. Several discon-

Table 1. DETEX index.

	Type I non-lined spots	Type II lined and non-lined spots	Type III lined spots	Type IV round indications	Type V linear indications
DETEX	1	1	1	2	3

tinuity classes can be defined. In table 2 an exercise of classification based on test with a known fatigue discontinuity, inspected by certified experts, is shown. The index of each class increases when the difficulty of detection decreases. To assign a discontinuity to a class, an analytical formulation has been defined. The characteristic size of the discontinuity d (in mm), $\mathrm{D_{min}}$ or $\mathrm{L_{max}}$ in table 2, the inverse of the square root of the black light intensity I in $\mathrm{W/m^2}$), and the DETEX index are used as classification parameters. In the following the formulation obtained by the best fit:

$$C(x) = A_0 \left[\alpha e^{\beta \log(x)} \right] \ , \tag{3}$$

Table 2. Visibility level (DETEX) classification.

Class	Morphological Type	Dimension	DETEX
X1	I (1)	all D_{min}	0 or 1
	IV (2)	$D_{min} \leq 0.2$ mm	0 or 1
	V (3)	all L_{max}	0
X2	I (1)	$D_{min} < 2.5$ mm	2
	II (1)	$D_{min} < 1.5$ mm	2
	II (1)	$D_{min} < 3.5$ mm	1
	III (1)	all L_{max}	1
	IV (2)	$D_{min} \leq 0.2$ mm	2
	V (3)	all L_{max}	1
X3	I (1)	$D_{min} > 2.3$ mm	2
	II (1)	1.5 mm $\leq D_{min} < 2.3$ mm	2
	III (1)	1.5 mm $\leq L_{max} \leq 2.3$ mm	2
	IV (2)	0.2 mm $< D_{min} \leq 0.8$ mm	2
	V (3)	$L_{max} = 2.3$ mm	2
X4	II (1)	2.3 mm $\leq D_{max} \leq 3.5$ mm	2
	V (3)	$L_{max} \geq 3.5$ mm	2
X5	III (1)	$L_{max} \geq 2.3$ mm	3
	V (3)	$L_{max} = 2.3$ mm	3

where C is the class index, $A_0[\cdot]$ is the integer operator (it takes real numbers and returns the integer part of them), $\alpha = 0.44$, $\beta = 0.87$, and $x = \text{DETEX} + 4d + 8\sqrt{(I)}$ a linear combination of the classification parameters. As expected, class index increases when DETEX and discontinuity dimension increase and black light intensity to detect the discontinuity decreases. Starting from ≈ 10 W/m^2, the influence due to the intensity of black light becomes negligible.

4.1. *PoD and process sensibility*

The inspection process sensitivity is defined as the discontinuities detection capacity related to the inspected materials, the number of inspector personnel, inspective materials (Penetrant, Emulsifier, Developer, Solvents), their application and parameters process. The Alenia approach is devoted to estimate the inspection process sensitivity, by determining the PoD. The PoD should be defined for each type of inspected material in the process considered. Typically the types of material are listed below:

Material Type	STANDARD
AL (league of Alluminium)	7075T73 not-plated
TI (Titanium and its league)	6Al-4V
S (Steel)	series 300

4.2. *Standards manufacturing*

For each type of material at least 15 standards should be manufactured, with dimensions between 80 mm and 300 mm and thickness between 2 mm and 5 mm. For each type of material, with the exception of some (from 2 to 4) standards without discontinuity, a number of discontinuity (from 2 to 10) should be realized with a depth less than 1 mm, open to the surface (e.g., fatigue cracks). In the following a method to generate discontinuity (generation fatigue) is described:

- use raw with thickness of 4-6 mm;
- select a square of side of between 80 mm and 300 mm;
- select a point in the square to achieve the discontinuity;
- apply in this point a stress through a punch, with constant cycles of loading;
- monitor the zone and wait for a sufficient time (typically corresponding to 15000-40000 cycles);
- mill the part along the edge;
- remove at least 2 μm thick and wash with de-ionized water.

Standard classification procedure: according to Alenia technical specifications NTA94151/-1 [5] and NTA94151/-2 [4] and [3], after standard processing, it is necessary:

a) to inspect the standard in the inspection cabin, with ambient illumination light less than 5 lx (lx is the SI unit of illuminance and luminous emittance), and at a distance of 100 mm from the standard;
b) to put the standard at a distance from the Wood's lamp so that an intensity less than 0.4 W/m^2 is measured on its surface;
c) to identify all the relevant visible information, indicating type and dimension, to record indications – a level of visibility equal to 3 will be given to them (DETEX);
d) to bring gradually the standard near Wood's lamp. Just an indication is visible, to indicate the type and shape of the corresponding sizes measuring the black light intensity (to fix relative visibility level: DETEX); to record indications.
e) to classify each discontinuity according to figure 1 and table 1.

4.3. *PoD and process sensibility determination*

1. Inspection.
   According to Alenia technical norms NTA94151/-1 [5] and NTA94151/-2 [4] and [3] the inspection procedure of standards must be approved by Level III [1]. Each inspector fulfill the standards inspection, filling a

report where the revealed discontinuity are listed along with any uncertainty or dubious case; it is not allowed to reprocess locally the ambiguous cases. At the end of each inspection, it is possible to proceed with the PoD determination.

2. Detecting frequencies determination.
   For each class of discontinuities X_j and for each inspector i, we have the total numer $S(X_j, i)$ of the detected discontinuities of class X_j found by the ispector i-th, so that it is possible to compute the Detecting frequencies $F_R(X_j, i)$ according to the following formula

$$F_R(X_j, i) = \frac{S(X_j, i)}{N_j} \ , \tag{4}$$

   where N_j is the total number of defects X_j for all classes $X_j, j = 1, 2, \ldots D$, $D = 5$ in our case see table 2.
3. Cumulative frequency $F_R(X)$.
   Moreover, we can compute the Cumulative frequency $F_R(X)$ according to the rule:

$$F_R(X_j) = \sum_{i=1}^{K} F_R(X_j, i) \ , \tag{5}$$

   where K is the operators total number.
4. For each class of discontinuity we get an estimate of the PoD

$$PoD(X_j) = \frac{F_R(X_j)}{K} \ , \tag{6}$$

   as well as the standard deviation

$$\sigma(X_j) = \sqrt{\frac{1}{K-1} \sum_{i=1}^{K} [F_R(X_j, i) - PoD(X_j)]^2} \ . \tag{7}$$

5. Determination of the confidence threshold 95% (under a Gaussian hypotesis) $T(X_j)$.
   Furthermore, the confidence threshold 95% $T(X_j)$ can be fuond by the formula:

$$T(X_j) = PoD(X_j) - 2\frac{\sigma(X_j)}{\sqrt{K}} \ . \tag{8}$$

   In literature, $T(X_j)$ as a function of X_j is known as the PoD's graphics of the related process. Note that in the last four formulas $j = 1, 2, \ldots, D$.

6. Estimate of the process sensibility.
An estimate of the process sensibility is given by the value $S(X_j)$ given by

$$S = \sum_{j=1}^{D} c(j)T(X_j) \quad \text{with} \quad \sum_{j=1}^{D} c(j) = 4 \ , \tag{9}$$

where D is the number of classes and $c(j)$ is the class X_j specific weight that grow when the class index decreases. The standard normalization to the maximum value of 4, for $c(j)$ is used in analogy to the "classical" penetrants sensibility's classification (this is a part of the process sensibility), according to the table 3. As a rule of thumb, the values of $c(j)$

Table 3. Penetrants sensibility's classification

1/2	Very low
1	Low
2	Medium
3	High(this is used in aeronautics)
4	Ultrahigh

are given by the following relations

$$c(j) = \frac{4}{\sum_{j=1}^{D}(D+1-j)}(D+1-j) \quad \text{for} j = 1, 2, \dots, D \ . \tag{10}$$

Individual performance.
An estimate of the i-th inspector individual performance can be determined on the basis of the partial sensibility defined by

$$S_i = \sum_{j=1}^{D} c(j)F_R(X_j, i) \quad \text{for} i = 1, 2, \dots, K \ . \tag{11}$$

To get the mentioned estimate we take the following steps:

By a permutation of indexes we rewrite the S_i in decreasing order, that is $S_1 \geq S_2 \geq \cdots \geq S_K$).
Then we compute the cumulative partial sensibilities $SC(h)$, $h = 1, 2, \dots, K$ according to the formula:

$$SC(h) = \frac{1}{h}\sum_{k=1}^{h} S_k \quad \text{for} \quad h = 1, 2, \dots, K \ . \tag{12}$$

Note that, owing to the ordering $S_i \geq S_{i+1}$, $i = 1, 2, \dots, K-1$ we also have that $SC_h \geq SC_{h+1}$, $h = 1, 2, \dots, K-1$.

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Because of this ordering property, the difference between $SC(1)$ and $SC(K)$ is an indicator of the dependency of the process sensibility on the individual performance. The greater is the this difference, the higher is the process sensibility.

4.4. *A case study*

Here we report a case study where 27 samples (leagues of) Titanium were inspected by 5 NDI inspectors. The statistics reported in table 4 were computed by the formula (11). Now, by using the data from table 4 we can

Table 4. Sum of the defects detected by the each inspector (i) for each morphological class, see figure 1.

i	$S(X_1, i)$	$S(X_2, i)$	$S(X_3, i)$	$S(X_4, i)$	$S(X_5, i)$
1	17	14	13	9	6
2	20	15	12	11	7
3	17	14	12	11	7
4	19	17	13	11	7
5	17	14	12	11	7

compute the values $F_R(Xj, i)$ according to the formula (4) and reported in table 5. In our case the partial sensibility of the inspectors can be computed

Table 5. Detecting frequencies.

i	$F_R(X_1, i)$ with $N_1 = 27$	$F_R(X_2, i)$ with $N_2 = 21$	$F_R(X_3, i)$ with $N_3 = 13$	$F_R(X_4, i)$ with $N_4 = 11$	$F_R(X_5, i)$ with $N_5 = 7$
1	0.63	0.67	1.00	0.82	0.86
2	0.74	0.71	0.92	1.00	1.00
3	0.63	0.67	0.92	1.00	1.00
4	0.70	0.81	1.00	1.00	1.00
5	0.63	0.67	0.92	1.00	1.00

according to the formulas (10)-(11). In this way we get the following values: $S(1) = 3.015552$, $S(2) = 3.288021$, $S(3) = 3.089079$, $S(4) = 3.401764$, and $S(5) = 3.089079$. In our case study the permutation of indexes used, in order to put the $S(i)$, $i = 1, 2, \ldots, 5$ in decreasing order, is given by $(1, 2, 3, 4, 5) \rightarrow (4, 2, 3, 5, 1)$. An evaluation of the individual performance of each inspector ($K = 5$ in our case) is computed by the formula (12). Hence, the following data can be found: $SC(1) = 3.401764$, $SC(2) = 3.344892$, $SC(3) = 3.259621$, $SC(4) = 3.216985$, and $SC(5) = 3.176699$.

On account of the small variation between $SC(1)$ and $SC(5)$, we can conclude that the process sensibility does not depend upon the individual performance. In table 6 we report the Pod, standard deviation, and partial sensibilities for each class of defects, computed by the formulas (6), (7), and (8), respectively. By the data reported in table 6, the overall sensibility of

Table 6. PoD, standard deviation $\sigma(X_j)$, and confidence threshold at 95% $T(X_j)$.

	X_1	X_2	X_3	X_4	X_5
PoD	0.67	0.70	0.95	0.96	0.97
$\sigma(X_j)$	0.02	0.03	0.02	0.00	0.00
$T(X_j)$	0.62	0.64	0.92	0.96	0.97

the process, according to the formula (9) is given by $S = 3$ and it represents the High level more often used in aeronautics.

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