The Advantages of Multiplex Testing

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Abstract. Nondestructive testing is a casual process, the result of which should be described with likelihood characteristics. One of the key parameters of the testing is the detect probability of a defect. It has been demonstrated that performance of the repeated testing by one operator or several operators with one method or several methods allows to detect the larger number of defects. The appropriate equation has been obtained, which allows to calculate the increase of probability of defect detection in the process of the repeated testing. It has been demonstrated the opportunity of a likelihood estimation of defect quantities in the testing object in accordance with the results of the limited capacity testing.

Development of the nondestructive testing (NDT) goes in a direction from application of the elementary one-parametrical techniques through expansion in the number of used parameters to multiparameter and at last to the holographic technologies [1].

Increasing the number of used testing parameters (operating frequencies, paths and modes of scanning, angles of radiographic or ultrasonic beams, etc.) increases the quantity of the receiving information, and their assembling to one system transits NDT to new quality. One of the earlier offers in NDT for increasing its informative capabilities was the offer on usage of a multifrequency location in ultrasonic testing [2]. It has appeared that the usage of several frequencies allows to enlarge the probability of defect detection essentially. Approaches formulated in [2] one can use in the estimation of the advantages of the repeated testing.

Intuitive conceptualization about usefulness of the repeated testing not always can be used for the proof of necessity to carry out it. Therefore good evidences are required, that will confirm that the repeated testing procedure with using of one method or several methods helps to detect more defects, allows thus to improve such important NDE parameters as probability of defect detection (POD - Probability of Detection), reliability of the testing and other parameters.

The defect detection in a testing object in itself is a random event. It is connected with plurality of operating factors. For different NDT methods these factors are various. But the surprising fact is the majority of NDT methods have close dependencies of probabilities of defect detection on the sizes of these defects.

Consider next with reference to ultrasonic testing (UT). Sizes of the defects, their position, forms of defects, their orientation, attenuation of ultrasonic waves in a material, characteristics of the probe and the equipment and a considerable body of other factors including qualification of an operator and his psychophysical state, have an influence on the detection of discontinuities during of UT.

As is known, the UT is being carried out with moving of the probe on the surface of a testing object. This process is named as scanning. A quantity of defects is being detected in the process of each scanning in case of their presence in the object. But practically all defects are never detected. Not only minor defects can be missed, but sometimes the defects, which have an influence on the integrity of the object, are not being detected.

One of the major parameters of the UT is the amplitude of echo-signal (for an echo-technique). Amplitudes are the random variables and to the full can be described only by the likelihood characteristic that is the distribution of amplitudes. Pictures of dispersion of signal amplitudes over the defect sizes in the process of ultrasonic testing are shown on Fig. 1, 2 for an example [3, 4]. From the figures follows the NDT gives out rather uncertain results in some cases.

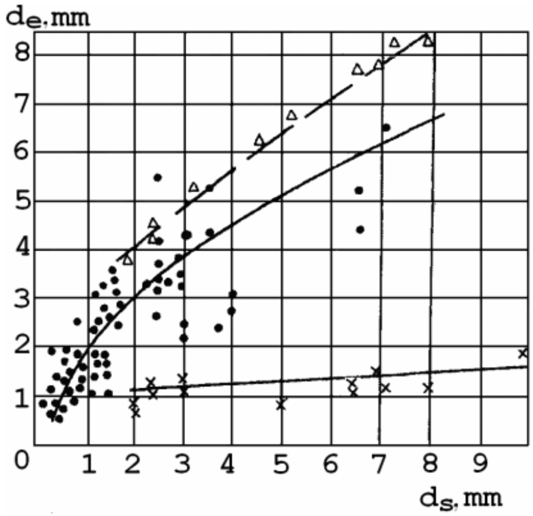

Figure 1. Correlation between of equivalent diameter d_e and its true size d_s: ● - volumetric defects; ×, Δ - cracks at measurement with single ultrasonic probe and under the "tandem", respectively [3].

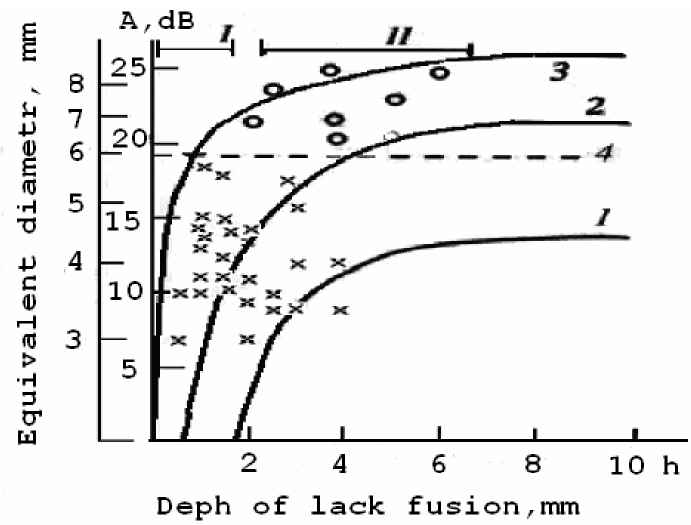

Figure 2. Dependence of echo-signal amplitude on the depth of lack of penetration (nonpenetration) for a single probe (f = 2,5 MHz, and $\beta = 30^0$) [4].

The data presented on the figures 1-2 testify the following: traditional (routine) techniques in the process of UT (as well as in other NDT methods) have inadmissible dispersion of readings (the measured dimensions of defects) under up-to-date requirements. The sizes of it may be spaced from fractions of millimeter up to tens of millimeters. The mistake may come up to hundreds percents. Just the same it occurs with probability of detection.

An estimation of the exceedance by signal amplitude of some level (that is a threshold level) P_e is required when the defect detection is considered. Non-exceedance of the threshold level cases by signal amplitude meet with probability of P_{ne}. When many defects, which have a certain distribution on the sizes, we get as well distribution on the signal amplitudes.

In case of the single testing a quality index of the testing is the number of detected defects - $n_{1.}$ By the way the detection occurs with corresponding probabilities of P_e.

Other sets of defects can be detected in the process of the repeated and the subsequent testings. The detection occurs in the moments of a casual exceedance by signal amplitude over a threshold level (caused by the defect). At the definition of the signal exceedance probability of a threshold level when there is even one defect in the object the full group of events (at the unitary testing) consists of two events:

I – an accidence over the threshold level when there is the defect detection;

II – a non-exceedance over the threshold level, i.e. the defect losses (non-detection).

Let's designate the probability of a defect detection as $P_{d.}$(probability of detection) and the probability of non-detection as $P_{nd.}$ (when the signal does not stand out above the threshold level that is the defect skip probability). As far as the defect detection and non-detection of the defect constitutes the exhaustive events, then:

$$P_d + P_{nd} = 1. \qquad (1)$$

For the unitary testing this is $P_d = P_e$ и $P_{nd} = P_{ne}$.

There can be four variants when the repeated testing:

I – the defect is being detected both in the process of the first testing and in the process of the repeated (second) testing;

II – the defect is being detected in the process of the first testing but does not come to light in the process of the second testing;

III – the defect is being detected in the process of the second testing but does not come to light in the process of the first testing;

IV – the defects are not being detected neither in the process of the first testing nor in the second testing.

Favorable events will be those which correspond to defect detection at least at one testing, that are events I, II and III.

When repeated testings are uncorrelated, then the events of the exceedance or non-exceedance over the threshold level are independent. The probabilities for the groups of the events in the process of double-checking have the following values:

$$\begin{aligned} &\text{I} — \text{P}^{\text{I}} = P_e \cdot P_e; \\ &\text{II} — \text{P}^{\text{II}} = P_e \cdot P_{ne}; \\ &\text{III} — \text{P}^{\text{III}} = P_{ne} \cdot P_e; \\ &\text{IV} — \text{P}^{\text{IV}} = P_{ne} \cdot P_{ne}. \end{aligned} \qquad (2)$$

The total probability of a signal detection due to the exceedance of a threshold level even if by one signal (i.e. reception of signals) in the process of double-testing, is equal:

$$P_d\,(2) = \text{P}^1 + \text{P}^{\text{II}} + \text{P}^{\text{III}} = P^2_e + 2P_e \cdot P_{ne}, \qquad (3)$$

but the defect skip probability (non-detection) is equal:

$$P_d\,(2) = \text{P}^{\text{IV}} = P^2_{ne}. \qquad (4)$$

In view of that $P_{nd} = 1 — P_e$ for each case, then:

$$P_d\,(2) = P^2_e + 2P_e \cdot (1 — P_e) = 2P_e — P^2_e. \qquad (5)$$

Using this scheme one can obtain the detection probability at large quantity of testings. In the process of the repeated testing should be considered to all cases of the defect detection and the defect skip that complicates the scheme of reasoning and corresponding calculations.

In view of that the complete group of events constitute the events of the defect detection P_d and the defect skip P_{nd}:

$$\left.\begin{aligned} P_{\mathrm{d}} + P_{\mathrm{nd}} &= 1 \\ \text{and} \quad P_{\mathrm{d}} &= 1 - P_{\mathrm{nd}} \end{aligned}\right\} \quad (6)$$

In addition, $P_{\mathrm{nd}} = (P_{\mathrm{ne}})^m$ at any numbers of testings, then the probability of defect detection in the process of the repeated testing can be obtained in another more simple way.

For instance using the formulas (2) & (6) for the double-testing we shall obtain:

$$P_{\mathrm{d}}(2) = 1 - (P_{\mathrm{ne}})^2 = 1 - (1 - P_{\mathrm{e}})^2 = 2P_{\mathrm{e}} - P^2_{\mathrm{e}}. \quad (7)$$

For three time testing we shall obtain:

$$P_{\mathrm{d}}(3) = 1 - (P_{\mathrm{ne}})^3 = 1 - (1 - P_{\mathrm{e}})^3 \quad (8)$$

For quadruple testing we shall obtain:

$$P_{\mathrm{d}}(4) = 1 - (P_{\mathrm{ne}})^4 = 1 - (1 - P_{\mathrm{e}})^4 \quad (9)$$

And for m-testing we shall obtain:

$$P_{\mathrm{d}}(m) = 1 - (P_{\mathrm{ne}})^m = 1 - (1 - P_{\mathrm{e}})^m \quad (10)$$

The indexes (2, 3, 4, m) for the probability of signal missing which are in formulas (7) - (10) are connected with usage of the theorem of product probabilities for independent results of the testing. Specifically signal missing takes place only if in the process of an each m-testing we do not detect a defect, i.e. $\mathrm{P}_{\mathrm{nd}}(m) = (\mathrm{P}_{\mathrm{ne}})^m$.

Using the formula (10) one can estimate increase of the probability of defect detection at any number of testings. Figure 3 shows a dependence of the probability of detection on the number of testings. The probability of detection in the process of the unitary testing $P_{\mathrm{e}}(1)$ serves as a parameter for these curves.

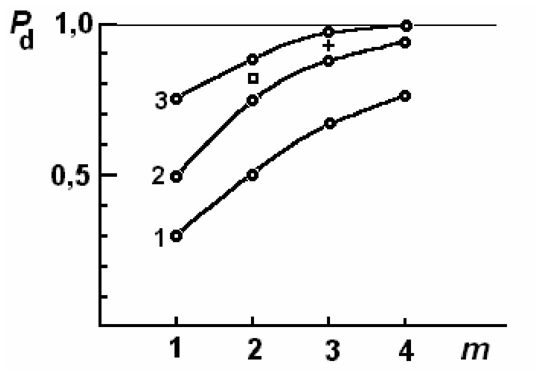

Figure 3. Dependence of the probability of defect detection P_e on the number of statistically independent testings (the number of attempts) m. 1 is initial (for $m = 1$) probability $P_e(1) = 0{,}3$; 2 is initial (for $m = 1$) probability $P_e(1) = 0{,}5$; 3 - initial (for $m = 1$) probability $P_e(1) = 0{,}75$; • -are two testings with various probabilities (P_1=0,3, P_2=0,75); + - three testings with various probabilities ($P_{1e}(1) = 0{,}3$, $P_{2e}(1) = 0{,}5$, $P_{3e}(1) = 0{,}75$).

In case the probabilities differ for each testing and are equal to P_1, P_2, …, P_m respectively, then the total probability of defect detection can be estimated as follows:

$$P_{\mathrm{d}} = 1 - (1 - P_1) \cdot (1 - P_2) \cdots (1 - P_m) \quad (11)$$

Formulas (10) and (11) can be used for the repeated testing with applying of both one NDT method and various NDT methods with different abilities of defect detection.

Figure 3 shows the calculations of the multiplay testings results with various initial probabilities. We notice, that for the double and triple testing, executed by two operators (the result is marked as a square) and by three operators (the result is marked as a criss-cross), the total probability of defect detection exceeds 0,8. Despite, the probability of defect detection for each operator taking part in the testing is less than 0,8.

The repeated testing allows to increase detecting probability of both each defect and the set of defects.

As an experimental supporting of the obtained formulas one can see Figure 4 taken from [5]. The shape of curve 1 completely coincides with shape of the curves shown on the figure 3. It should be noted that the curve 2 essentially differs from "standard" curves for reasons undefined. Perhaps some unknown to us conditions of the experiment cause this difference.

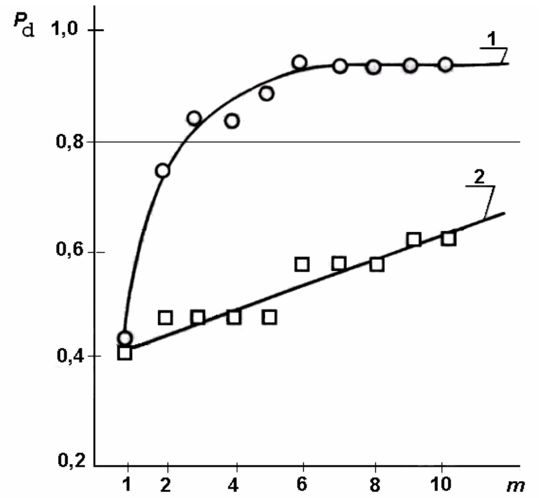

Figure 4. Dependence of the defect detection on the number of testings (1) carried out by different NDT Inspectors (2) [5].

The correct approach to the execution of the testing is that up to the start of testing process it is necessary to know the initial probabilities of defect detection. It demands preliminary greater efforts and fulfillment of significant methodical researches. It is necessary to know reliability of a used testing technique, conformity of the operator qualification to the testing requirements (i.e. reliability of the operator) and in addition, to use the state-of-the-art equipment with the instruction of quality parameters of the nondestructive testing aids.

Nowadays these requirements are practically impracticable in full. As a rule, all we know only is a quantity of the detected defects after of the unitary or the repeated testing. However, one can estimate some parameters (the supposed number of defects in an object in particular) with using the described approach.

Let’s consider some interesting opportunities coming off equation (10).

After the unitary testing procedure in fact almost everything is unknown with one exception that is quantity of the detected defects. I.e. using the equation (10) after carrying out the single testing we shall obtain:

$$P_d(1) \approx (=)\ \frac{N_1}{N_x} = 1 - (1 - P_e)^{m=1} = P_e. \qquad (12)$$

This is one equation with two unknown arguments (P_d and N_x). The signs ≈ (=) mean an approximate correspondence or a conditional equality.

Then here is the equation for the second testing:

$$P_d(2) \approx (=) \ \frac{N_2}{N_x} = 1 - (1 - P_e)^{m=2} = 2P_e - \ P^2_e. \qquad (13)$$

Here is already the second equation with the same two unknown arguments. Now we substitute $P_e = \frac{N_1}{N_x}$ from the equation (12) to the equation (13) and then in simple way we shall obtain the equation connecting the unknown to us number of defects of the object with the number of detected defects after the first and the second testing, namely:

$$N_x \approx (=) \frac{N_1^2}{2N_1 - N_2}. \qquad (14)$$

Considering the equation (14) one can suppose three various situations:

$$\left.\begin{array}{l} 1.\ N_1 > N_2, \\ 2.\ N_1 = N_2, \\ 3.\ N_1 < N_2. \end{array}\right\} \qquad (15)$$

It is unlikely that the situation $N_1 > N_2$ corresponds to the case when the second testing has been executed “worse” than the first. As a rule, at least one or more additional defects should be detected in the process of the repeated testing. If it has not happened, i.e. $N_1 = N_2$ (the same defects have been detected), then this situation poorly corresponds to the absolute defect detection case. The situation $N_1 < N_2$ corresponds to a usual practice of the testing and in this case the equation (14) can be used rightfully.

Using the specified approach one can fulfill the estimations using the results of the succeeding testings, We mean the third, the fourth and etc.

It will be appreciated, what the obtained equation (14) is not the formula unequivocally defining the number of defects in the testing object. But it allows to estimate the possible number of defects on the results of several testings, in view of our understanding that practically it is impossible to detect all defects. Certainly, more profound analysis of these estimations and an absolute substantiation of the stated offer are required. Nevertheless, the described approach gives even any opportunity to estimate the general number of defects in the testing object using results of the real testing. The real testing is the impossibility in principle of detecting of all defects without exception. The understanding of this situation and the fair attitude to it will allow us to make one more step toward the completion of transition from "static" defectoscopy to "stochastic" defectometry.

References

[1] Nondestructive testing and diagnostics: Reference book/V.V.Klyuyev, F.R.Sosnin, A.V.Kovalev, and others; under the editorship of V.V.Klyuyev. The second edition corrected & added, - Moscow: Mashinostroenie, 2003. – 656 pp.

[2] Ivanov V.I. Parameter of multifrequency ultrasonic defectoscopy. Defectoscopy, 1978, # 1, 62-67.

[3] Scherbinsky V.G. Technology of the ultrasonic testing of the weldments. Moscow: Tisso, 2003, - 326 pp.

[4] Voronkov V.A., Ermolov I.N. Measuring of the root-crack height with two UT probe. Defectoscopya. 1990, #11, 7-13.

[5] Hetman A.F., Kozin U.N. Nondestructive testing and operation safety of vessels and pipelines of pressure. Moscow: Energoatomizdat, 1997. –288 pp.