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METHOD AND PROCEDURE FOR CHECKING THE ACCURACY OF THE SCAN-INDEXING SYSTEM OF THE NDT-UT EQUIPMENT FOR IMMERSION TECHNIQUE

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ABSTRACT

This paper deals with the proposal of a method and procedure to verify the accuracy of the scanning-indexing system of the NDT-UT facility for immersion technique, using comparison with a plate of aluminum alloy plate, processed as a test plate

KEYWORDS: transducer, ultra-sounds, flat bottom hole, test plate, immersion technique, encoder, DA converter, coupling.

1. Introduction

In the non-destructive testing of aluminum alloy plates, using ultrasounds, there are generally used two techniques, i.e.: contact ultrasonic testing where the ultrasonic transducer is brought into physical contact with the controlled material and immersion ultrasound control where the ultrasonic transducers move near the material being controlled while this is immersed in the working fluid, which is called coupling.

The coupling used in immersion technique is generally water which has undergone demineralization treatment, mechanical filtration of particles, corrosion inhibitor treatments (sometimes this treatment may be absent) and ultraviolet sterilization treatments or other methods. Also the coupling temperature is monitored and controlled to ensure consistency of the utilization properties.

Ultrasonic nondestructive testing facility, using the immersion technique, features high accuracy and is productive for materials with big dimensions. In order to move ultrasonic transducers throughout the surface of the material to control and to be able to identify and accurately store the coordinates of defects, a so called scanning and indexing system is needed to ensure the required accuracy.

This system, present in all nondestructive ultrasonic immersion technique facilities is mostly automatic and can move the transducers in the horizontal plane formed by X and Y axes of the facility. Being responsible for detecting the coordinates of the defects found by the transducers, one might seriously question the accuracy of the measurement provided by that system, both onto the scanning direction (longitudinal axis X) and onto the indexing direction (transverse axis Y). Therefore specifications such as [2] and [3] contain acceptance criteria as regards its maximum permissible error, ie ± 2.5 mm for both X axis and Y axis. Obviously, to show compliance with this requirement it is necessary to evaluate the measurement accuracy of the scanning - indexing system

The metrology issue of assessing the accuracy of the measurement, in general, and that associated to scanning – indexing systems, in particular, raises a number of technical difficulties and additional costs. In this context, this paper proposes a practical method and procedure for assessing the accuracy of scanning and indexing to satisfactorily overcome these difficulties.

2. Difficulties and costs

To solve the problem posed by the necessity of knowing the accuracy of scanning and indexing, it is necessary first to identify the main difficulties which arise in this problem.

A first category of problems to be solved is related to setting a budget of uncertainty associated with scanning and indexing respectively, the budget including factors which cause significant errors in determining the X and Y coordinates (see Chapter 5) [1], [4]. Another category of issues raised in determining the accuracy of scanning and indexing refers to the formulation of a working procedure able to cover the budget of uncertainty. All these elements require specific expertise of the specialists who perform the assessment of accuracy, an expertise which is generally not available in any organization that operates NDT-UT-immersion facilities. That is why generally specialized laboratories or manufacturers resort to this type of equipment.

The costs associated with scanning and indexing accuracy assessment are according to the authors' experience, quite high. An example could be the cost calculated from the necessary measurement points. Thus, a number of measuring points is about 40, and if the charges applied from the list of the official rates of the Romanian Bureau of Legal Metrology, the entire cost of the assessment would be about 2,000 Ron (650 USD) for each installation. If this check is run quarterly, its annual cost may rise to 8,000 RON (2,600 USD).

Where accuracy assessment should be conducted by a provider outside the country, these costs would double, exceeding 5,000 USD annually for each facility inspected. This cost would add the other costs of verification for such a facility, adding an extra effort to support the operating costs. Hence, any effort to solve the problem of assessing the accuracy of scanning and indexing by the metrological department of the organization that operates one or more immersion ultrasound inspection facilities presents a real practical interest.

3. Description of the scanning – indexing system

The figure 1 below illustrates the operating logic of the ultrasound inspection system type USL SCM 12X.

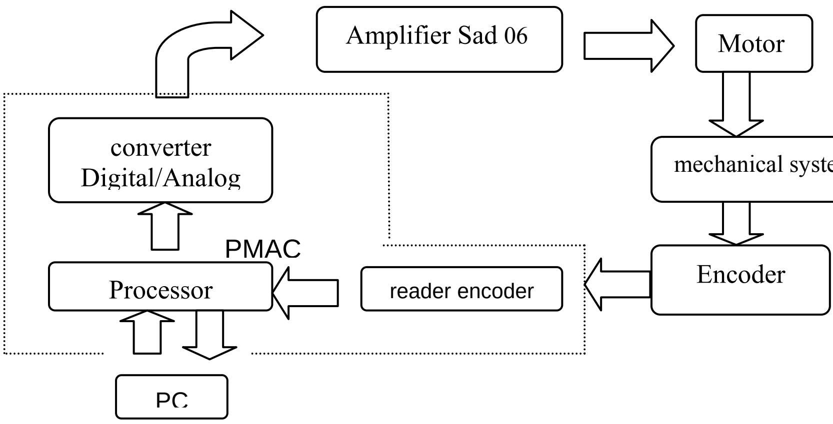

***Fig. 1.** Block diagram of scanning –indexing system of the facility - type USL*

***Fig.2.** Head transducers, seven unfocused transducers (rectangular) and a focused transducer (circular shape)*

***Fig. 3.** Test plate for verifying the accuracy of the scan-indexing system*

The mechanical system allows the movement over X, Y and Z axes. During the inspection of the product (aluminum alloy plate), Z axis position of the transducers head remains constant and is determined by ensuring a certain water path of the ultrasound waves. Moving the transducers head is transmitted by the operator through commands to the PC through a specialized software. The PC sends the command to the digital-analog converter, and the analog signal is sent to the amplifier which drives the electric motor. The rotational movement of the electric motor is converted into translational motion by the mechanical system by means of a pinion-rack mechanism for the X axis, respectively screw-nut mechanism for Y and

Z axes. The position of the transducers head along the axes is measured by the encoders attached to each traveling mechanism. The encoders send the signal under the form [no. pulses / mm] to an encoder reader that processes information for the processor. The processor compares the value of the traveling command with the value received from the encoder and decides whether the reading head has arrived to the prescribed destination or not. Also, if the transducer head detects a discontinuity in the material being controlled, its coordinates are stored by the PC based on the value calculated from the signal of the encoder.

4. Describing the method of assessing the accuracy of the scanning indexing system

From the metrology viewpoint, the scanning-indexing system is part of the equipments for measuring „lengths", a range widely approached by the specialists, but whose conventional methods used for the calibration of „classical" measuring equipment become useless because of the features resulted from the particular combination of dimensional aspects and the ultrasonic transducer issues and also the big system size. To overcome the technical difficulties detailed in Section 2, the authors propose a specific method and procedure for checking the compliance with the applicable requirements[3], and which are characterized by simplicity, very low implementation costs and, last but not least, the reduced measurement uncertainty. The proposed method is based on the evaluation of errors by means of which the transducers system of the facility identifies a specific location of coordinates (X, Y) defined/measured by the mechanical system of the facility traveling within the ultrasonically investigated range, thus combining the electrical-mechanical system measurement performance to travel and identify the scanning head position (see Fig. 2) with the performance of the transducers system to accurately locate a specific disruption of the material being inspected. The novelty introduced by this method is to embed both systems - displacement / measurement system and transducers system - into the whole scan-indexing system.This approach is accounted for by the fact that the final target of the scan-indexing system is to accurately (±2.5 mm, conf. [2], [3]) identify the position of each disruption found in the product under investigation.

5. Budget of uncertainty associated with the method proposed

Preliminary consideration on the budget of uncertainty; the sources of error related to the components of the uncertainty budget associated with the proposed procedure are as follows:

1. errors contained in the coordinate information (i_{iX}, i_{iY}) – such errors shall be assessed by coordinate measurements carried out during the investigation procedure;
2. errors due to operator (i_{op}) – fall within the concept of repeatability and reproducibility;
3. errors of indication (i_{ind}) – they are due to the limited number of decimals as reported by the measurement and the corresponding inherent rounding;
4. errors due to mechanical gears (i_{mec}) – they are due to the order of rack- gear wheel clearance provided by the construction of the scanning-indexing system;
5. errors of positioning (i_{poz}) – refer to the positioning of the transducer head the bottom plate hole whose coordinates are being determined and are influenced by the ratio of hole size and actual size of the ultrasound beam;
6. errors of calibration/standard (i_{etalon}) – they are introduced by the uncertainty known to each dimension represented by the standards used to verify the test plate. The amount of uncertainty is reflected in the standards certificates or in those of the coordinate measuring machine (CMM) which served as reference for the transmission of measuring units;
7. errors due to temperature variation (i_{term}) – the temperature variation determines, by expansion /contraction, dimensional modifications of the test plate. Out of the error sources listed above, i_{ix} and i_{iy} are included into the measurements carried out for inspection purpose, while the error due to temperature variation within the working space is of the order $\alpha_t\Delta_t$, where the heat expansion coefficient for Al α_t= 23,6µm/(mK), and the temperature in the working space is kept within the limits 15° ÷ 25°C, which, combined with a maximum plate size of 2500 mm, corresponding to an error not exceeding 0.3mm.

As regards the positioning error i_{poz}, this is a possible error to locate the defect center - which is the order of the defect radius considered, namely 0.6 mm for the minimum defect corresponding to the inspection class A [3]. Errors i_{mec} due to the gear clearance of the scan-indexing system can be assessed as no greater than 10% of the tooth thickness measured on the division diameter, this value being considered no more than 0,4 mm. The error due to the operator must be dissociated from the error to equipment and therefore will not be included into the uncertainty budget of the scanning- indexing system.

The total error for the measurements in the X and Y axes is given by equations (1) and (2).

$$E_X = l_{ix} - l_S + L_S\alpha\Delta t + \delta_{i\ poz} + \delta_{i\ mec} + \delta_{i\ ind} \qquad (1)$$

$$E_y = l_{iy} - l_S + L_S\alpha\Delta t + \delta_{i\ poz} + \delta_{i\ mec} + \delta_{i\ ind} \qquad (2)$$

Table 1 provides briefly the corresponding uncertainty budget equations (1) and (2).

Table 1. *Budget of uncertainty for the scan-indexing system*

Size V_i	**Estimate value** v_i	**Standard Uncertainty** $u(v_i)$	**Type of Distribution**	**Sensitivity coefficient** c_i	**Contribution to uncertainty** $u_i(y)$	**Type of assessment**
i_X	$\overline{i_X}$	s_X	normal	1	$s_X\ c_i$	A
i_Y	$\overline{i_Y}$	s_Y	normal	1	$s_Y\ c_i$	A
i_{etalon}	l_{etalon}	0.006 [mm]	rectangular	-1	0.006 [mm]	B
i_{term}	0	2.04 [K]	triangular	2.5 [m] X 23.6 [µm/mK]	0.120 [mm]	B
i_{poz}	0	0.346 [mm]	rectangular	1	0.346 [mm]	B
i_{mec}	0	0.115 [mm]	rectangular	1	0.115 [mm]	B
i_{ind}	0	0.029 [mm]	rectangular	1	0.029 [mm]	B

In the last column of this table it is indicated the type of evaluation, according to [4], by means of which each component of the budget is estimated.

Thus, the type of assessment A involves determining, by statistical calculations, the standard deviation of that error while for type B the value of the standard uncertainty value is estimated based on the characteristic values and the type of statistical distribution of the error.

6. Description of work procedure

The procedure that makes it possible to implement the method described in Section 3 uses an aluminum alloy plate - similar to products currently under examination with ultrasounds - which was highly accurately processed to become a test plate (see figure 3).

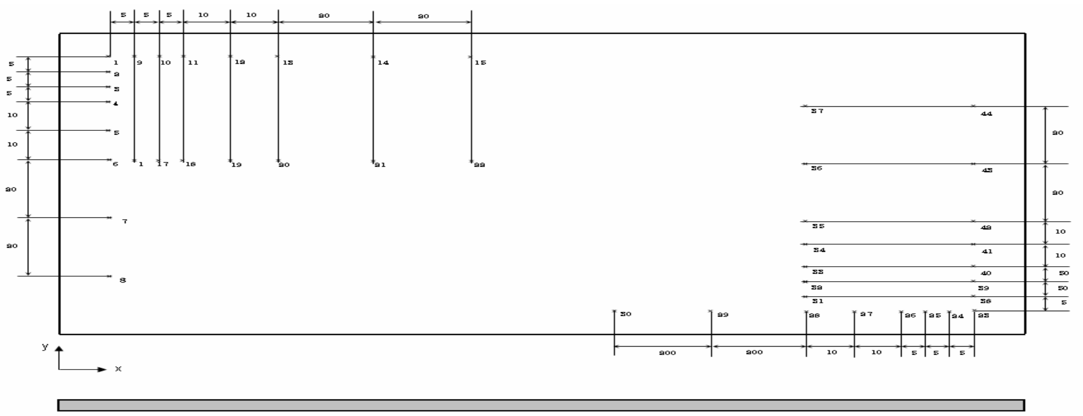

Fig. 4. *Test plate, sized length x width x thickness = 2231mm x 1169mm x 40mm.*

The processes referred to are meant to make discontinuity as flat-bottomed hole (FBH) to the established positions with an accuracy much higher than it is to be evaluated. If the accuracy specified for scan-indexing system is ± 2.5 mm and the coordinate values are provided by the scan-indexing system with a resolution of 0.1 mm, the test card processing with an accuracy of ± 0.01 mm was considered satisfactory. The test plate processing consisted of a series of flat-bottomed holes, arranged in rows and columns, the distances between rows and columns evenly distributed over the measurement range of scanning and indexing system. These holes are the calibration points needed to assess the accuracy of the scanning – indexing. Processing is done by drilling and boring on a machine tool with a numerical coordinate control (CNC), the depth of the holes being 20 mm and their diameter of 1.2 mm. The choice of the diameter of 1.2 mm corresponds to FBH defect type with maximum size allowed for class A of inspection [4]. Measuring distances between holes is performed by a coordinate measuring machine (CMM) whose measurement accuracy is defined by an expanded uncertainty value of max. ± 0.01 mm. Following these measurements a certificate of calibration for the test plate is drawn up.

After drilling the holes, they are clogged with epoxy resin to prevent water penetration, so as to prevent damage by corrosion of the inner surface of the discontinuity thus created. Test plate is shown in Figure 4. Test plate is immersed into the water tank of the facility to be scanned. The scanning process takes place automatically and includes the defects coordinates as detected by the scanning head.

After completion of the scan, the report is printed, recorded in the facility computer which contains coordinates of all defects detected during the scan operation. These data are compared with the standard values of the calibration of the test plate and the measurement error is obtained by comparing the standard value of the measured value.

6.1. Determining the measuring accuracy

To determine the measuring accuracy it is calculated:

1. The arithmetical average of the errors from the measurements made on each axis of movement *X* and *Y*, denoted E_X and E_Y.

2. The standard deviation of the errors obtained by measurements on each movement axis *X* and *Y,* denoted s_X and s_Y is calculated.

s_x = standard deviation of the errors from the measurements made on X axis, as expressed by relation (3):

$$s_x = \sqrt{\sum_{i=1}^{n}(x_i - E_X)^2/(n-1)} \quad (3)$$

s_y = standard deviation of the errors from the measurements made on Y axis, as expressed by relation (4):

$$s_y = \sqrt{\sum_{i=1}^{n}(y_i - E_Y)^2/(n-1)} \quad (4)$$

3. Calculation of standard uncertainty of the measurement performed with scanning-indexing system for each axis of movement X and Y, denoted by u_x and u_y, where:

$$u_x^2 = s_x^2 + u^2_{ietalon}(x) + u^2_{iterm}(x) + u^2_{ipoz}(x) + u^2_{imec}(x) + u^2_{iind}(x) \quad (5)$$

$$u_y^2 = s_y^2 + u^2_{ietalon}(y) + u^2_{iterm}(y) + u^2_{ipoz}(y) + u^2_{imec}(y) + u^2_{iind}(y) \quad (6)$$

4. Calculation of expanded uncertainty of measurement performed with scanning-indexing system for each axis of movement X and Y, for a 95% confidence level, denoted by U_x *and* U_y by relations (7) and (8):

$$U_X = 1.96\ u_x \quad (7)$$

$$U_Y = 1.96\ u_y \quad (8)$$

Note: The accuracy of scan-indexing system is characterized by an extended uncertainty to determine the errors calculated from direct comparison between the test plate and the scan-indexing system.

The inspection conclusion is that the scan-indexing system is „accepted" if U_X < 2.5mm and if U_Y < 2.5mm.

If the calibration result is "rejected" it shall be determined the root cause and necessary corrective actions are taken to satisfy the accuracy requirement.

7. Example of calculation

To give an example, it will be considered verifying the accuracy of the scan-indexing system presented in Section 3, using the proposed procedure.

In this regard, Tables 2 and 3 are used for measurements on the X and Y axes.

The tables are filled in as described below:

- in the first column of tables 2 and 3 it is recorded the point on the test plate that is considered conventional origin for the test points in column 3
- in the second column of Tables 2 and 3 it is recorded the movement axis for which inspection is carried out
- in column 3 of Tables 2 and 3 it is recorded the points where measured lengths are compared to the standard ones.
- in column 4 of Tables 2 and 3 it is recorded the values measured by the scan-indexing system between the points recorded in the 3rd column
- in column 5 of Tables 2 and 3 it is recorded the standard values from measuring the test plate by means of the coordinate measuring machine (CMM).
- in column 6 of Tables 2 and 3 it is recorded the errors values calculated by discounting the standard value from the measured value.
- in column 7 of Tables 2 and 3 it is recorded the values of the extended uncertainty obtained by multiplying the standard uncertainty by 1.96.

It is calculated the arithmetic average of the errors obtained from the measurements made on X axis:

$$E_X = 0.012\text{ mm.} \quad (9)$$

Table 2. *Values of the measurements carried out for X axis*

Conventional origin point	**Inspected axis**	**Length between points**	**Measured value** [mm]	**Standard value** [mm]	**Error** [mm]	**Extended uncertainty** [mm]
1	X	1÷16	50.00	50.00	0.00	1.166
		16÷17	50.00	49.97	0.03	
		17÷18	50.00	49.99	0.01	
		18÷19	100.00	99.98	0.02	
		19÷20	100.00	99.96	0.04	
		20÷21	200.00	199.98	0.02	
		21÷22	200.00	199.99	0.01	
		5÷9	50.00	50.00	0.00	
		9÷10	50.00	49.98	0.02	
		10÷11	50.00	49.97	0.03	
		11÷12	100.00	99.98	0.02	
		12÷13	100.00	99.97	0.03	
		13÷14	200.00	199.96	0.04	
		14÷15	200.00	199.97	0.03	
23		29÷30	200.00	199.99	0.01	
		28÷29	200.00	200.01	-0.01	
		27÷28	100.00	100.02	-0.02	
		26÷27	100.00	100.01	-0.01	
		25÷26	50.00	50.00	0.00	
		24÷25	50.00	50.00	0.00	
		23÷24	50.00	50.02	-0.02	

It is calculated the arithmetic average of the errors obtained from measurements made on the Y axis:

E_Y = -0.003 mm. (10)

It is calculated the standard deviation of the errors obtained from the measurements made on X-axis, expressed by relation (3)

s_X= 0.018 mm. (11)

Table 3. *Values of the measurements taken on Y axis*

Conventional origin point	**Inspected axis**	**Length between points**	**Measured value** [mm]	**Standard value** [mm]	**Error** [mm]	**Extended uncertainty** [mm]
1	Y	1÷2	50.00	50.00	0.00	1.156
		2÷3	50.00	50.00	0.00	
		3÷4	50.00	49.99	0.01	
		4÷5	100.00	100.00	0.00	
		5÷6	100.10	100.05	0.05	
		6÷7	199.90	199.94	-0.04	
		7÷8	200.00	200.00	0.00	
		23÷38	50.00	50.01	-0.01	
		38÷39	50.00	50.02	-0.02	
		39÷40	50.00	50.00	0.00	
		40÷41	100.00	99.98	0.02	
		41÷42	100.00	100.04	-0.04	
		43÷44	200.00	199.98	0.02	
		37÷36	200.00	199.99	0.01	
23		36÷35	200.00	199.98	0.02	
		35÷34	100.00	100.04	-0.04	
		34÷33	100.00	100.03	-0.03	
		33÷32	50.00	49.99	0.01	
		32÷31	50.00	50.01	-0.01	
		31÷27	50.00	50.01	-0.01	

It is calculated the standard deviation of the errors obtained from the measurements made on *Y* axis*,* as expressed by relation (4):

s_Y = 0.023mm (12)

The standard uncertainty for the measurements made on X axis is expressed by relation 5:

$u_x^2 = 0.018^2 + 0.006^2 + 0.170^2 + 0.346^2 + 0.115^2 + 0.029^2 = 0.144$ [mm^2] or $u_x = 0.380$ [mm]. (13)

The extended uncertainty for the measurements made on X axis is expressed by relation 7:

$U_x = 1.96\, u_X$ = 1.96 x 0.380 [mm]= 0.745 [mm] < 2.5 [mm] (14)

It follows that the scan-indexing system meets the accuracy requirement for the movement axis *X.*

The standard uncertainty for the measurements made on Y axis is expressed by relation (6):

$u_y^2 = 0.023^2 + 0.006^2 + 0.170^2 + 0.346^2 + 0.115^2 + 0.029^2 = 0.144$ [mm^2] or $u_y = 0.380$ [mm]. (15)

The extended uncertainty for the measurements made on *y* axis is expressed by relation (8):

$U_y = 1.96\, u_Y$ = 1.96 x 0.380 [mm] = 0.745 [mm] < 2.5 [mm] (16)

It follows that the scan-indexing system meets the accuracy requirement for the movement axis *Y*.

8. Conclusions

The proposed method and procedure have a number of features that were highlighted, at least in terms of key issues, in Sections 2-7 of this paper. Thus, a number of conclusions may be drawn with respect to the method and procedure proposed herewith.

a).The budget of uncertainty associated with the proposed method is richer than the usual one in that it includes the source of errors due to detection of calibration points by the ultrasonic transducers.

b).The procedure is based on measuring the relative position of calibration points, thus avoiding the additional uncertainties related to the origin of the facility axes system.

c).The performance obtained by applying the procedure is influenced by the accuracy of the location of the test plate in the immersion tank, parallel to the facility coordinate axes. In practice, this positioning is achieved by exploiting the constructive elements of the immersion platform and is corrected by making a preliminary scan of the test plate, after which the plate outline is visible on the facility screen.

Location correction is performed so that the contour of the plate test is straight (not stepped) and clear (no shadows).

d).The costs incurred by the proposed procedure are limited to cost of test plate, the labor of scanning, uncertainty calculation and editing the verification certificate. Given that the test plate can be made from a scrapped plate for discontinuities and other internal defects that more often than not, organizations that operate such equipment have the processing capacity required, these costs are much lower than those of verification by an external provider.

e).The proposed procedure and the results of its implementation have been considered acceptable by all NADCAP auditors and all customers who assessed it on the occasion of the audit at ALRO SA Slatina.

Summarizing the foregoing, it can be stated that the proposed procedure and implicitly the method this is based on, are simple and reasonably accurate, practical and inexpensive, which recommends then for industrial practice.

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