

THICKNESS MEASUREMENT UNCERTAINTIES OF AEROSPACE PARTS BY ULTRASONIC: EXPERIMENTAL STUDY

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Abstract: The main purpose of this paper is to describe the thickness measurement of aerospace parts by nondestructive ultrasonic method and discuss the results obtained from an experiment in order to identify the source of measurement errors and metrological uncertainties from the process.

Key words: measurement uncertainty, metrology, ultrasonic, aerospace structures.

1. INTRODUCTION

Ultrasonic testing has been practiced for many decades. Thickness gauging of industrial parts is an example application of this test where instruments have been refined to make data collection easier and better [1]. Techniques derived from the use of ultrasound are used in several areas, especially applications in health and nondestructive testing [2].

In the aerospace industry, for example, several aircrafts stop its service to carry out detailed inspections of their structural members and systems, including the power plant. The stop to maintenance of the aircraft is responsible for ensuring the correct operation of all components and to provide security, comfort and not to affect the punctuality of the services. Among several maintenance services to be performed in the aircraft during a check, the corrosion prevent and control is the one of the most important since it includes methods of inspection and tasks to prevent corrosion in all aircraft areas, such as fuselage, wings, stabilizers, flight control surfaces etc. During a routine inspection, when a discrepancy is detected, some actions must be immediately taken in order to correct the problem and avoid the loss of structural strength.

Corrosion is a major enemy of aircraft maintenance, since it reduces the structural member integrity and, if not corrected in time, may result in loss of member and flight safety. The general procedure of corrosion removal in structural members consists in identifying the affected member thru aircraft maintenance manual, removing the damage using a proper procedure, visually inspecting and performing nondestructive inspections. After corrosion removal, the remaining thickness gauging is carried out in order to estimate the portion of material that was lost. It will enable to verify the remaining static and fatigue strength of the affected part, but firstly, the values have to be compared

with allowable limits as stated in technical manuals and aircraft maintenance handbooks.

In the general procedure, the steps related with remaining thickness measurement by ultrasonic testing and results assessment are the critical steps. They require extreme care since can contain several errors coming from not estimated uncertainties of the measurement procedure, resulting in a wrong decision by technician or engineer.

This paper discusses the use of ultrasonic method for remaining thickness gauging of an aircraft structural member after corrosion removal, and also the inspection findings through an experiment objected to detect sources of uncertainties in the ultrasonic measurement. In addition, this paper studies those uncertainties, how they may reflect on the professional decision and establish a comfort zone of measurement results.

2. EXPERIMENT

2.1. General

Thickness gauging using ultrasonic test is based on the time taken by the ultrasonic pulse inside the specimen. The condition to allow a correct measurement is a constant sonic velocity within the specimen.

For all process of thickness gauging by ultrasonic, a reference standard must be used. The test results are, however, achieved when the instrument is calibrated in a reference standard block manufactured with the same material of the part being tested. Refer to Figure 2.1.

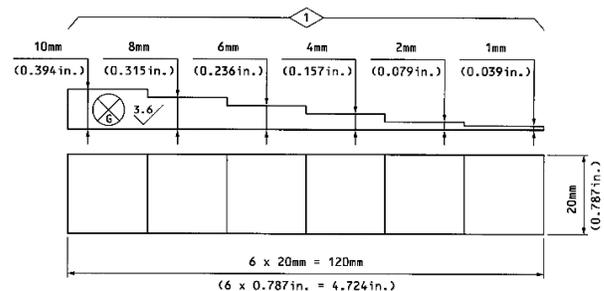


Figure 2.1. Reference standard block [5].

To provide the thickness measurement of a part by ultrasonic, the instrument generates an electrical initial pulse

at first which is led to the transmitter element of the probe where it is converted into a mechanic ultrasonic pulse. Using a couplant, the ultrasonic pulse is transmitted from the probe to the material to be tested through which it passes at a velocity typical of that material until it encounters a change in the material. Part of the pulse energy is reflected from this point and returned to the probe (echo). If the signal reaches the backwall of the test object before this, the reflected pulse is called backwall echo [3]. Refer to Figure 2.2.

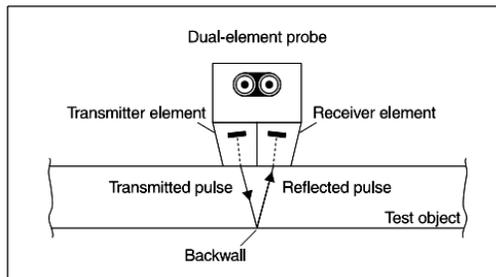


Figure 2.2. Thickness measuring using a dual-element probe [3].

2.2. Relevant source of errors

Several sources of error are present in a thickness measurement by ultrasonic, such as temperature (by affecting the sound velocity of the material), probe selection, couplant usage, operator training, process knowledge, adequate method of calibration etc.

2.3. Instrument calibration

From the calibration, it can be identified the confidence of a measurement device or reference standard, comparing the results of calibration with standard specifications. To calibrate an instrument, it is necessary to express the uncertainty associated with the numerical result declared, considered a key parameter in quantifying the quality of the final measurement result [2].

In the aerospace industry, the thickness measurement by ultrasonic is widely used with dual-element probe. Using a dual-element probe, the best instrument calibration is obtained by taking as reference two points of value. These points must be a value above and one below the nominal thickness of the part to be measured. The value of the nominal and its tolerances must be known through engineering drawings.

As mentioned before, the sonic velocity of the part being measured varies with the temperature of material. This implies that the instrument must be calibrated using a reference standard block immediately before the inspection begins, in fieldwork, so that the removal of the reference temperature is minimized. After the calibration procedure, the instrument is ready for use.

2.4. Experiment overview

When a structural damage is reported in an aircraft during routine inspections, some standard procedures must be performed in order to identify the damaged structure, if it is a principal structural element (P.S.E.) or a secondary element, and the correct assessment of the damage. If the damaged structure is a P.S.E., it will directly affect the flight safety. The Figure 2.3 shows a typical damage by corrosion in an Airbus A300 airplane. This damage, when detected, requires an immediate action to clean up and control the corrosion on order not to affect the structural integrity of the member and consequently the flight safety. The damages exposed in the Figure 2.3 are located on the upper skin of the right wing and were caused due to dissimilar material contact (material of fastener with material of skin) in presence of moisture. Flaws in the surface of protection provided such contact causing corrosion.

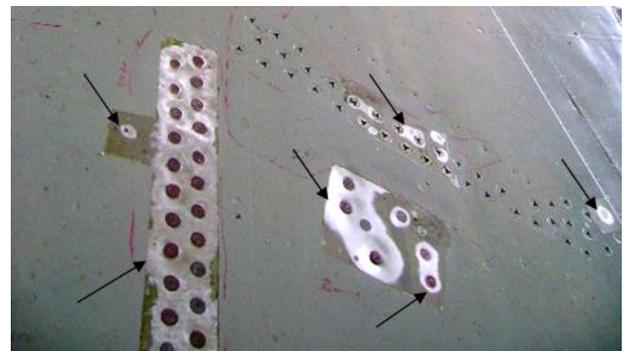


Figure 2.3. Corrosion detected in several areas of upper surface of an aircraft wing. Areas later reworked.

The procedure of corrosion removal is described on the specific Structural Repair Manual of the aircraft [4], which basically consists of removing the surface protection (decorative paint and epoxy base primer), removal of fasteners installed in the affected area, sanding the corroded area to remove all evidences of corrosion, smoothing the rework surface contour, measurement of remaining thickness by ultrasonic inspection and assessment of findings. The procedure for remaining thickness measurement is stated in the "Nondestructive Test Manual" of the aircraft [5]. The procedure of corrosion removal, cleaning up and smoothing of rework surface is known as blend out. The Figure 2.4 shows a typical shape of a plate after blend out procedure.

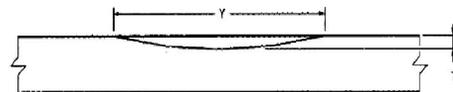


Figure 2.4. Blend out, where T= Removed material, Y= Rework length and Y must be greater or equal to 40T.

2.5. Experiment uncertainties and measurements

VIM [6] describes the measurement uncertainty as a non-negative parameter that characterizes the dispersion of the values attributed to a measurand, based on used data. The measurement uncertainty includes components coming from systematic effects such as components associated with corrections and values assigned to standards, as well as definitional uncertainty. Sometimes estimated systematic effects are not corrected, but, instead of this, associated components of measurement are embedded.

The study listed some sources of uncertainty inherent in the thickness measurement by ultrasonic inspection in reworked areas located at upper surface of the aircraft wing. These uncertainties may directly affect the measurement results.

Unlike the usual procedure, were randomly chosen three areas in the affected surface of the wing. It was drawn a grid of 10 x 10 mm and performed seven measurements with ultrasonic instrument in each square of mapping, totaling 189 measurements. The Figure 2.5 and 2.6 show the time of the measurements. After this procedure, it was observed the point with the highest dispersion values.



Figure 2.5. Remaining thickness measurement by ultrasonic inspection. Several readings in a 10 x 10 mm grid.



Figure 2.6. Remaining thickness measurement by ultrasonic inspection.

This point was chosen to make for the calculations of uncertainty according to ISO GUM [7]. The Table 2.1 shows the values found after readings. ISO GUM [7] method allows to determine the expanded uncertainty of the process and establish a comfort zone for the technician or

engineer who will assess the readings and define the actions to be taken to maintain the flight safety of the airplane.

Table 2.1. Ultrasonic measurements of the point with the highest dispersion – Results.

x	Remaining surface thickness of reworked area (in inches)
1	0,695
2	0,698
3	0,700
4	0,698
5	0,704
6	0,698
7	0,697
Mean \bar{x}	0,698
Standard Deviation $S(x)$	0,00282

For acceptance of the measured values it was used the Chauvenet Criterion thru Equation (1).

$$r^* = \frac{|x_i - \bar{X}|}{S(x)} \quad (1)$$

Where r^* is the index to be found, x_i is the value to be tested, \bar{X} the mean of sample and $S(x)$ the standard deviation. Chauvenet Criterion states that:

$$r^* > R_C \quad (2)$$

Where R_C is the rejection limit of Chauvenet.

From the Table 2.1 was extracted the values with the highest dispersion. In the experiment, the value 0,704 is considered suspect due to its dispersion in face of the mean of sample. Testing this value by Chauvenet by Equation (1) we found 1,925028 inches. Applying the Equation (2):

$$1,925028 > R_C \quad (3)$$

Checking the Table 2.2 for comparison of R_C :

Table 2.2. Chauvenet Rejection Limits.

n	2	3	4	5	6	7	10	15	25	50	100
R_c	1,15	1,38	1,54	1,65	1,73	1,80	1,96	2,13	2,33	2,57	2,81

For $n = 7$, $R_C = 1,80$. Then,

$$1,925028 > 1,80 \quad (4)$$

Then, the value 0,704 must be removed from the sample since it was disapproved by Chauvenet.

A new table (Table 2.3) is written without the value excluded by Chauvenet.

Table 2.3. Ultrasonic measurements of the point with the highest dispersion – Results excluding the value rejected by Chauvenet.

x	Remaining surface thickness of reworked area (in inches)
1	0,695
2	0,698
3	0,700
4	0,698
5	0,698
6	0,697
Mean \bar{x}	0,697667
Standard deviation $S(x)$	0,001633

For less than the error can be present, it is always present in any measurement [8]. During the measurement process, several sources of uncertainty can come up and must be checked, since they can influence on a component acceptance after evaluation. In the study, this main sources of uncertainty are coming from the ultrasonic instrument resolution, due to the removal of reference temperature (20°C), due to the statistic (Type A) and uncertainty inherited from reference standard block. The Equation (5) describes the statistic uncertainty, known as type A, associated to the mean of readings.

$$S(x) = i_A = \frac{S(x_i)}{\sqrt{n}} \quad (5)$$

The Equation (6) describes the uncertainty due to the removal of reference temperature.

$$i_t = \frac{l_{0p} \cdot \Delta\alpha \cdot \Delta T}{\sqrt{3}} \quad (6)$$

The Equation (7) describes the uncertainty inherited from reference standard block.

$$i_h = \frac{i_p}{k_p} \quad (7)$$

The Equation (8) describes the uncertainty due to ultrasonic instrument resolution.

$$i_r = \frac{r}{2\sqrt{3}} \quad (8)$$

Applying all equations described above, it is obtained the uncertainties contained in the process.

After knowing all uncertainties, it is possible to calculate the combined uncertainty u_c through Equation (9), assuming the coefficients of sensitivity (c) are equal to 1:

$$u_c = \sqrt{i_A^2 + i_t^2 + i_r^2 + i_h^2} \quad (9)$$

Knowing the valor of u_c , it is possible to calculate the number of effective degrees (ν_{eff}) through Equation (10) as described below:

$$\nu_{eff} = \frac{u_c^4}{\frac{u_A^4}{n-1} + \frac{u_r^4}{\infty} + \frac{u_h^4}{\infty}} \quad (10)$$

Table 2.4. Values of coverage factor k for distribution – t for degrees of freedom ν in function of confidence [8].

Degrees of freedom	P= 68,27	P= 95,45	P= 99,73
35	1,01	2,07	3,23
40	1,01	2,06	3,20
45	1,01	2,06	3,18
50	1,01	2,05	3,16
100	1,005	2,025	3,077
∞	1,000	2,000	3,000

From the Table 2.4 it is extracted the approximate value of k :

$$k = 2,05 \quad (11)$$

Knowing the value of k it is possible to calculate the expanded uncertainty U through Equation (12):

$$U = k \times u_c \quad (12)$$

Then,

$$R = (0,697667 \pm 0,002546) \text{ inch. for } k = 2,05$$

3. RESULTS

In the study several aspects could be observed and tested. Among these aspects, some were relevant for the

measurement results and others were unimportant to the process. A random point was chosen to be used as base for variations of standard experiment. For each variable, it was taken three readings.

It was observed the mode of action of each operator who performed the measurements, especially with regard to the pressure applied on the probe during the measurement. When little pressure is applied to the probe, no significant reading variation was found. Refer to Table 3.1 for findings.

Table 3.1. Ultrasonic readings in a random point varying the pressure on the probe.

Reading	Little pressure applied	Medium pressure applied	A lot of pressure applied
1 st	0,752''	0,750''	0,750''
2 nd	0,752''	0,751''	0,750''
3 rd	0,752''	0,750''	0,750''

It was also observed the influence of the amount of couplant in the measurement process. It was noticed that the amount of couplant has little influence in the procedure. Refer to Table 3.2 for findings.

Table 3.2. Ultrasonic readings in a random point varying the amount of couplant.

Reading	Small quantity	Medium quantity	A lot of quantity
1 st	0,751''	0,750''	0,750''
2 nd	0,750''	0,752''	0,751''
3 rd	0,751''	0,751''	0,751''

The operator was also observed. The readings were taken with three different operators. It was noted that the most experienced operator did not vary the measurements, while the other two operators, less experienced, varied their measurements. Refer to Table 3.3 for findings.

Table 3.3. Ultrasonic readings in a random point varying the operator.

Reading	Operator 1	Operator 2	Operator 3
1 st	0,752''	0,751''	0,751''
2 nd	0,752''	0,751''	0,750''
3 rd	0,752''	0,752''	0,751''

Still, it was confirmed that the temperature change induces an unreliable measurement result. Firstly, the equipment was calibrated inside a room at a temperature of 21°C. Shortly after the experiment was performed on the airplane with the results as per Table 3.4

Table 3.4. Ultrasonic readings in a random point varying calibrating the equipment in a room at 21°C and after field measurement at 28°C.

Reading	Operator 1
1 st	0,752''
2 nd	0,753''
3 rd	0,754''

When the equipment is calibrated and measured in field (at the same temperature as the part, 28°C) the variation becomes smaller. Refer to Table 3.5 for findings.

Table 3.5. Ultrasonic readings in a random point calibrating the equipment in the same temperature as the part to be inspected (T= 28°C).

Medição	Operador 1
1 ^a	0,750''
2 ^a	0,750''
3 ^a	0,751''

It was also noted that the surface finish of reworked area influences the results, since the better finish becomes in a more accurate result.

The experiment also shows that the largest influence on the results (expanded uncertainty) came from the uncertainty inherited from the reference standard block. This shows that when we have a more accurate reference standard, more accurate the process will be.

The difference between the crystal transducer dilatation and the reference standard was not taken into account in this experiment, and the inherited uncertainty coming from the certification of calibration of the ultrasonic equipment.

Tolerance is a value that expresses the difference between the maximum and the minimum dimensions that a certain size must present without compromising the functional requirements of the part with that dimension [8]. Taking the limit (+0,005 inch) and minimum (-0,003 inch) of the skin thickness (as per production drawing):

Nominal thickness after rework is 0,698 inch.

Upper dimension is 0,703 inch.

Lower dimension is 0,695 inch.

The tolerance (t) is the difference between the upper dimension and the lower dimension [8], as per Equation (13):

$$t = D_s - D_i \quad (13)$$

$$t = 0,703 - 0,695 = 0,008 \text{ pol.} \quad (14)$$

To check the suitability or not of a measurement system, we compare their measurement uncertainty with the tolerance of the process, provided that the errors present in the system are minimized [8]. The ideal condition is pointed out that:

$$U = \frac{1}{10} \cdot t = \frac{1}{10} \cdot 0,008 = 0,0008 \text{ pol.} \quad (15)$$

and

$$U = \frac{1}{3} \cdot t = \frac{1}{3} \cdot 0,008 = 0,00266 \text{ pol.} \quad (16)$$

According to [9], the zone line must take into account the value of measurement uncertainty as shown in Figure 3.1.

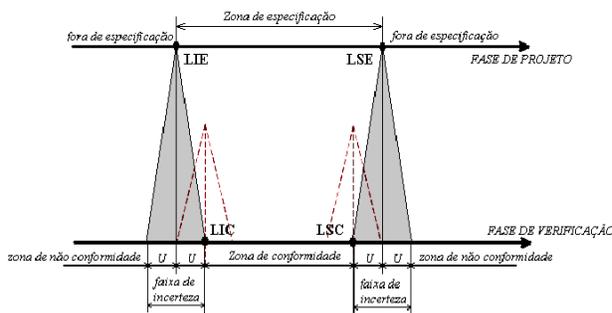


Figure 3.1. Comparison between measurement uncertainty and process tolerance.

With this experimental study we can noted that a equational model must be used to establish a zone line taking into account the production tolerance and the uncertainties coming from the process. Doing like this, the technical evaluator will be fully able to approve or reject a rework in accordance with allowable limits in the manufacturer technical manuals. This method prevents the situation when the rework is out of boundary values as per zone line and this has not been taken into account, which could result in an airplane returning to service out of the requirements required by national and international regulatory agencies of aviation.

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