The calculating procedure for measurement uncertainty using ultrasound testing

THE CALCULATING PROCEDURE FOR MEASUREMENT UNCERTAINTY USING ULTRASOUND TESTING

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Abstract - Measurement errors and uncertainties frame a theory used more and more in the industrial domain, especially in the quality engineering department. The main reason underlying this is that there is a very big demand in characterising the measurement results as complete and correct as possible. This is a requirement found in the standard ISO 17025 that translates into “General requirements for the competence of testing and calibration laboratories” specifying that along with the results of the measurement uncertainties should be estimated, also. This article outlines the procedure for calculation of measurement uncertainty for defect characterization highlighted through the method of ultrasonic nondestructive testing.

Keywords: measurement uncertainties, measurement errors, non-destructive testing, ultrasound examination, procedure for calculation of measurement uncertainty.

1. Introduction

In the activity of a testing laboratory using non-destructive methods, examination reports in which the conditions and results of measurements are mentioned must contain information on the measurement uncertainties of these results.

Measurement uncertainty is calculated taking into account a number of sources of errors that might affect the measurement to highlight the contribution of each of them on the final result and on the total measurement uncertainty. The terms "error" and "uncertainty" should not be confused because, although they seem similar, they represent different concepts. Errors are those that affect the measurement, bringing changes to the final outcome, whereas uncertainty is the one that quantifies the accuracy with which the measurement result was determined.

Knowledge of measurement errors and measurement uncertainties is of high importance because, according to them, a series of elements are established, like: the functionality of the pieces, their life span, the evolution of the defect found in the pieces, and so on.

2. The calculating procedure for uncertainty measurement

The procedure provides general requirements and guidelines for expressing uncertainty results for ultrasonic non-destructive testing and recommends the general expression for the implementation and harmonisation of requirements with the national and international standards, on the measurement uncertainty.

Ultrasound testing are non-destructive examination methods that use the sound waves to identify various types of defects that may be present in the structure of the materials and pieces taking under consideration.

Measurement uncertainty calculation follows the methodology of calculation of SR ISO/IEC Guide 98-3. Measurement uncertainties, part 3: Guide to the expression of measurement uncertainty (GUM [8]). For evaluating and expressing the uncertainty of a result of a measurement several steps should be taken, as follows:

- All sources of errors which may affect the final result, contributing to the final measurement uncertainty should be expressed, as well as the standard uncertainties associated with each identified sources of errors;
- Calculation of the standard uncertainties associated with the sources of errors;
- Determining the combined uncertainty associated with the sources of errors;
- Determining the expansion factor used to calculate the extended uncertainty from the combined measurement uncertainty;
- Reporting the outcome of the measurement, along with the combined and expanded measurement uncertainty.

These phases will be presented in a more detailed way below.

a. Expressing sources of errors which may affect the final result, contributing to the final measurement uncertainty, as well as the standard uncertainties associated with each identified sources of errors;

The following table summarized the sources of errors, the way and the extent in which they affect measurements via their standard uncertainties.
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Table 1. Summary of the sources of errors and the standard uncertainties related

<table>
<thead>
<tr>
<th>No. Crt.</th>
<th>Source of error</th>
<th>Processing method of standard uncertainty – type A/Standard uncertainty values – type B - ( (u(x_i)) )</th>
<th>Uncertainty type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement errors due to the means of control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Errors due to calibration process</td>
<td>The standard measurement uncertainty shall be determined through statistical processing carried out the calibration readings.</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>Errors due to calibration block</td>
<td>( u(x_2) = 0.000625 ) Source: “Guidance Document for Estimation of Measurement Uncertainty in Non-Destructive Testing”, elaborated by SAC – SINGLAS laboratories in Singapore [4]</td>
<td>B</td>
</tr>
<tr>
<td>3</td>
<td>Data acquisition errors</td>
<td>Such errors are neglected, because one of the properties of the measuring apparatus is that it can store the data the observer needs and it has the possibility to store them in a digital format directly into its internal memory, and be later transferred to the computer.</td>
<td>B</td>
</tr>
<tr>
<td>4</td>
<td>Multiplication errors</td>
<td>These errors are neglected, because in carrying out the calculations, numbers with 5 decimal will be used, thus reducing to a minimum the measurement error due to this factor.</td>
<td>B</td>
</tr>
<tr>
<td>Measurement errors due to the human operator</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| 5 | Errors due to the measurement procedure | a. Choosing a measurement procedure that can be too generic 
\( u(x_{5a}) = 0.003 \text{ g}, \text{ where } g \text{ – thickness of the material} \) 
b. The experience of the operator 
\( u(x_{5b}) = 0.003 \text{ g}, \text{ where } g \text{ – thickness of the material} \) 
| 6 | Reading errors | Readings of the piece’s measurements will be statistically processed in order to obtain the standard measurement. | A |
| Measurement errors due to working conditions |
| Errors due to the equipments used |
| 8 | Errors due to the measuring apparatus | \( u(x_8) = 0.00095 \) This value is obtained from the calculation, evaluating sources of uncertainty of the defectoscope from its data sheet [9]. | B |
| 9 | Error generated by the probe response | \( u(x_9) = 0.001 \text{ g}, \text{ where } g \text{ – thickness of the material} \) 
| 10 | Errors due to probe alignment | \( u(x_{10}) = 0.002 \text{ g}, \text{ where } g \text{ – thickness of the material} \) 
| 11 | Linking systems between the probe and the measuring apparatus | Errors due to this source are neglected, considering that the linking systems are running normally, without significant errors. | B |
| Errors due to the piece that is being examined |
| 12 | Material type of the piece | \( u(x_{12}) = 0.0015 \text{ g}, \text{ where } g \text{ – thickness of the material} \) 
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<table>
<thead>
<tr>
<th>Condition of the surface of the piece</th>
<th>( u(x_{13}) = 0.003 \text{ g} ), where ( g ) – thickness of the material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating type of the piece</td>
<td>( u(x_{14}) = 0.0005 \text{ g} ), where ( g ) – thickness of the material</td>
</tr>
<tr>
<td>Geometry of the piece</td>
<td>( u(x_{15}) = 0.0005 \text{ g} ), where ( g ) – thickness of the material</td>
</tr>
<tr>
<td>Thickness of the piece</td>
<td>( u(x_{16}) = 0.003 \text{ g} ), where ( g ) – thickness of the material</td>
</tr>
</tbody>
</table>

Measurement uncertainties are differentiated into two main categories:
- Type A Uncertainty: processed by statistical analysis of strings of observations (through direct measurements);
- Type B Uncertainty: taken from other sources (data sheets, speciality literature, etc.).

In the calculation of measurement uncertainties, for different sources of errors resulting from direct measurements by reading and then processing them, it is recommended to use a number of minimum 5 measurements.

- Type B Uncertainty: calculated with the formulas described earlier for type B uncertainties and statistical calculations, for type A uncertainties. For statistical calculations, the phases that need to be taken into account are as follows:
  - The calculation of the arithmetic mean of the values obtained from direct measurements (for type A uncertainty):
    \[
    \bar{x} = \frac{1}{n} \sum_{k=1}^{n} x_k
    \]
  - Subtracting the arithmetic mean from each value read to determine the residual for each result (for type A uncertainty):
    \[
    \text{Residual} = (X_k - \bar{x})
    \]
  - Calculating the experimental variance (for type A uncertainty):
    \[
    s^2(X_k) = \frac{1}{n-1} \sum_{k=1}^{n} (X_k - \bar{x})^2
    \]
  - Calculating the estimated standard deviation \( s(X_k) \) equal to the positive square root of \( s^2(X_k) \) (for type A uncertainty):
    \[
    s(X_k) = \sqrt{s^2(X_k)}
    \]
  - Calculating standard uncertainty (for type A uncertainty):
    \[
    u(X_k) = c_k \cdot s(X_k)
    \]
  where \( c_k \) represents the correction applied to the experimental standard deviation according to the number of measurements.

Table 2 summarizes the value of correction factor depending on \( n \) - the number of measurements and \( k_p \) – the expansion factor. The expansion factor \( k_p \) is chosen depending on the confidence level of interest. Generally, it varies between 2 and 3, but for special applications, it can be outside this range.

<table>
<thead>
<tr>
<th>Correction factor, ( c_k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
<tr>
<td>8</td>
</tr>
</tbody>
</table>

c. Determining the standard combined uncertainty \( u(c(y)) \) for the result of the measurement, \( y \)
Standard combined uncertainty \( u(c(y)) \) associated with the measurement result shall be calculated in accordance with the relation below, being the square root of all contributions to the measurement error.
\[ u_c^2(y) = \sum_{i=1}^{n} u_i(x)^2 \]  

(6)

d. Determining the expansion factor used to calculate the extended uncertainty, based on the combined uncertainty \( uc(y) \)
The standard combined uncertainty, determined according to the previous relation can be assumed as such and attached to the examination review to be the uncertainty of the results obtained. However, most of the time, in most applications, it is opted to define a range in which a large proportion of the distribution of values are found and can be assigned to the measurand. This is called the extended uncertainty, it is noted with \( U \) and can be calculated by multiplying the standard combined uncertainty \( uc(y) \) with an expansion factor \( k_p \):

\[ U = k_p uc(k) \]  

(7)

Thus, an \([y - U : y + U]\) interval will be described, in which it is assumed that there is the true value of the measurand \( Y \), that is the distribution of the values which can be attributed to it, for a given level of confidence.

Table 3. Value of the expansion factor \( k_p \)

<table>
<thead>
<tr>
<th>Level of confidence [%]</th>
<th>Expansion factor ( k_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>68.27</td>
<td>1</td>
</tr>
<tr>
<td>90</td>
<td>1.645</td>
</tr>
<tr>
<td>95</td>
<td>1.960</td>
</tr>
<tr>
<td>95.45</td>
<td>2</td>
</tr>
<tr>
<td>99</td>
<td>2.576</td>
</tr>
<tr>
<td>99.73</td>
<td>3</td>
</tr>
</tbody>
</table>

e. Reporting the measurement result \( y \), along with the standard combined uncertainty \( uc(y) \) and the expanded uncertainty \( U \)

Each instrument is accompanied by an uncertainty and hence when you report the result obtained, it must be specified and associated uncertainty. This is necessary in order to determine the functionality of inspected thereafter. Thus, you may encounter the following situations:

- The piece may be missing or may have small defects, which do not significantly affect its functionality;
- The piece may have flaws, but they can be diminished through various methods, so that the piece to be used;
- The piece can have major flaws, becoming an unusable scrap.

Therefore, the examination reports shall contain all the information necessary to process the data and determine the results of the measurement and its uncertainty. This information must be representative of the type of measuring and destination of the piece inspected and, in general, they consist of:

- The definition of the measurand as accurate and as complete as possible;
- Description for the examination method used;
- Presentation of the readings;
- Description of the procedure of the calculation used for the measurement uncertainty;
- The full description of all sources of errors that affect the final result and the manner in which each was evaluated in order to determine the standard uncertainty afferent to them;
- Experimental data analysis and calculation of uncertainty of measurement for determination in a manner as easy to follow and modify, where necessary;
- Establishing all the parameters involved in the calculation, along with their sources and the reasons why they have been chosen (coefficients, confidence level, values of the standard type B uncertainty, etc.);
- Expressing the outcome of the measurement, together with afferent uncertainty.

3. Conclusions

This article enlarges upon a theoretical and experimental study on the calculation of the measurement uncertainty for non-destructive examinations using ultrasounds. The information presented in it may be used in any measurement laboratory and can in handy by using the data and the calculation relations presented. In the same time, there is a possibility that the data, respectively the values of type B uncertainty, to be adjusted on a case by case basis, depending on the operator’s judgement. Therefore, the procedure becomes a flexible one, from its utilisation point of view, which can be a real advantage.

The flexibility of the calculation procedure can be evidenced by the following ideas and conclusions:

- The non-destructive testing method using ultrasounds is one whose results are influenced by a considerable number of measurement errors. Sources vary also, so that the method is strongly affected by them. Therefore, it is difficult to control the measurement so that the measurement uncertainty is lower. For this reason and in accordance with the requirements of testing laboratories by the standards in use, it is very important that, together with the results of measurements to determine the measurement uncertainty which provides valuable information about the quality of the measurements made. Also, its knowledge facilitates taking decisions of acceptance and rejection, of the parts examined with ultrasounds;
- The procedure for calculating the measurement uncertainty is determined according to the SR standard ISO/IEC Guide 98–3. Measurement uncertainties. Part 3: Guide to the expression of uncertainty in measurement (GUM), regarding the steps that should be followed. However, in this calculation there are some factors which should be taken into account. First of all, not for all sources of measurement errors, the associated standard uncertainties can be quantified with values.
through direct measurements. Many of them require a base of knowledge and experience in order to be able to establish the standard uncertainty. This is the case type B uncertainties, whose values are taken from various sources of literature that contain such information, based on conclusive studies;

- In the calculation of measurement uncertainties there are several elements that can appear and that can be influenced in a big way by the interpretation each operator gives in this matter, due to its previous experience. Thus, using the same procedure, the final measurement uncertainty result may differ from an operator to another, with the possibility of variation of the following factors:

  - Readings made by each individual operator may be different, both because of the experience in these types of measurements and visual acuity;
  - Estimates of the number of direct measurements to be made, along with the confidence level that is considered, may lead to different values of the correction factor that is involved in the calculation of the standard type A uncertainties;
  - The values shown in this article for the calculation of type B uncertainties are not fixed values. These can be changed on a case by case basis, depending on your way of thinking, the current situation and experience of the operator which takes this calculation decision;
  - If the confidence level is not required to be of a certain value, its assessment can also generate differences in the outcome of the extended uncertainty through the value of the expansion factor.

Therefore, the calculation of uncertainty and everything that influences it may be interpretable from one person to another, and be carried to its end based on experience, also. However, it remains of the utmost importance that the following measurements to be able to quantify the quality of the results obtained.

- In this case, most of the uncertainty type B uncertainties, taken from the literature, are expressed through a relationship of calculation that depends on the thickness of the piece. They provide an approximate assessment of uncertainty information derived from these sources of error, but based on studies which support any non-destructive testing laboratory for ultrasound examinations.

Therefore, depending on the thickness of the piece being inspected, the standard type B uncertainties, may affect the final result in a much bigger way than type A uncertainties, if the thickness is big.

Otherwise, usually, type A uncertainties, that result from of direct measurements are those that will put a bigger footprint in the final uncertainty calculation. This is due to a larger number of reasons relating to both operators carrying out the measurements (experience, knowledge, Visual acuity, professional interest, etc.), and to the measuring apparatus, the piece itself or even the conditions of measurement.

Acknowledgements

This work was supported by a grant of the Romanian National Authority for Scientific Research, CNDI–UEFISCDI, project number PN-II-PT-PCCA-2011-3.2-0084."

4. References