Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 60 (2017) 326 – 331

www.elsevier.com/locate/procedia

27th CIRP Design 2017

Uncertainty Assessment for Measurement Processes in the Aerospace Manufacturing Industry

J. Rojo Abollado[1], E. Shehab[1*], M. Rose[2], T. Schröter[2]

[1]School of Aerspace, Transport and Manufacturing, Cranfield University, Cranfield, Bedfordshire, MK34 0AL, UK

*e.shehab@cranfield.ac.uk

[2]Mechanical Test Operations Centre, Rolls-Royce MTOC GmbH, Kiefernstraße 1, 15827 Blankenfelde-Mahlow, Deutschland

Abstract

Measurement processes are critical to the aerospace industry, which products must follow strict regulations and customer requirements. Additionally, measurement of uncertainty is fast becoming a requirement from both certification bodies and customers. An uncertainty assessment must be carried out for all processes that need to add an uncertainty statement to the measurement result. In order to maintain defined quality standards, aerospace manufacturing companies need to identify all measurement disciplines that benefit from stating the level of uncertainty and define a methodology to calculate it for complex measurement processes.
An extensive research has been conducted in order to define the most appropriate methodology to assess uncertainty on complex aerospace components and a case study has been applied to assess the strain gauge calibration test uncertainty of different aerospace components.
This study develops a generic framework, which helps the assessment of all individual sources of uncertainty and completes the one established by the Guide to the Expression of Uncertainty in Measurement. Conclusions have been extracted from the outcome of the case study.
The conducted research contributes to a better understanding of measurement processes and good practices that lead to lower uncertainty. The outcome will help manufacturing companies to be aware of the contributors of uncertainty to the tests, how to reduce this uncertainty and the reliability of the measurements taken during the process.

Peer-review under responsibility of the scientific committee of the 27th CIRP Design Conference

Keywords: Measurement of Uncertainty, Assessment framework, Key drivers

1. Introduction

Aerospace manufacturing companies need to establish measurement process regularly, but the establishment of a measurement process is complicated, as it requires a good linkage between the acquired expertise and the measurement data, in order to decide what is necessary to be measured [1].

Every measurement carried out has some uncertainty associated. This uncertainty of the measurement is the doubt that exists about the result of the measurement process and it should not be confused with the term error, which is the difference that exists between the measured value and the 'actual value' of the item measured, while uncertainty is a quantification of the doubt that exists related to the measurement result [2].

The reasons behind the need of assessing uncertainty are various; the main are the increase in quality of the measurements and the better understanding of the results. Other particular reasons could be the need of reporting the uncertainty of the measurement on a calibration certificate, or, in relation with tests the uncertainty is needed to determine a pass or fail. An additional use of measured uncertainty is the assessment of whether or not you are meeting a tolerance.

Peer-review under responsibility of the scientific committee of the 27th CIRP Design Conference
doi:10.1016/j.procir.2017.01.030

In order to have a complete measurement result, a statement of the uncertainty in it needs to be placed. For the industry, having really accurate measurements is crucial, as they represent a key source of decision making. Subsequently it needs to be understood that the reliability of each measure has to be high and clearly defined. That is why each measurement result should be linked to a measurement uncertainty value which represents the simplest way to express the reliability of the result [3].

Nevertheless, the concept of uncertainty as a quantifiable attribute is relatively new in the history of measurement [4] and only calibration laboratories are used to perform uncertainty evaluation for a long time. But currently, things are changing in the aerospace industry and measurement uncertainty is becoming progressively recognized by the testing community.

Nomenclature

UoM Uncertainty of Measurement
GUM Guide to the Expression of Uncertainty in Measurement
MoU Measurement of Uncertainty

1.1 Background

Measurement of uncertainty is an important concern for aerospace manufacturing companies. For the last years it has become a common requirement from both customers and certification bodies. This uncertainty represents the interval around the result of the measurement where there is a high probability to find the real value.

Standards are continually becoming more demanding in terms of Measurement of Uncertainty (MoU), in order to assure the quality and the security of the final product.

Sources of uncertainty are various and can come from the measuring instrument, item being measured, the measurement process (incomplete definition of the test procedure), the environment, operator skills (imperfect realisation of the test procedure), sample (not representative sample), imported uncertainties or other sources.

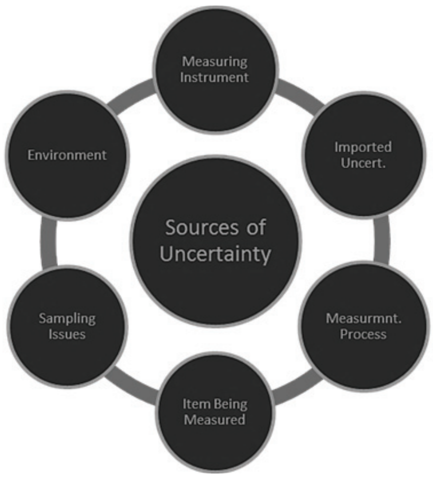

Figure 1: General Sources of Uncertainty

The quantification of each uncertainty source is a critical part in the calculation of uncertainty and it is currently one of the most challenging tasks in assessing the Uncertainty of Measurement (UoM). The sources of uncertainty are not necessarily independent and some or all can contribute to the variations in repeated observations.

Mistakes made by operators are not measurement uncertainties. They should not be counted as contributing to uncertainty and should be avoided by working carefully and by checking work.

1.2 Research Motivation

Conducting this research serves the aerospace industry in several ways. The most explicit benefits of measuring uncertainty are to:

- Give a starting point to improve existing measurement processes to become more efficient and cost-effective.
- Help the fulfilment of business requirements, as it is becoming a requirement from certification bodies and a need for internal and external customers.
- Reduce risks and improve credibility of tests results.
- Help the reduction of calibration costs.
- Bring new quantitative information on the measurement process and improve its understanding and reliability.
- May be requested by the customer to know the uncertainty associated with test results.
- Provide a competitive advantage. It promotes quality and adds value to the organisation.

The outcome of this study helps aerospace manufacturing companies to be aware of the contributors of uncertainty to the tests, how to reduce this uncertainty and the reliability of the measurements taken during different measurement processes.

2. Uncertainty Quantification

It is important to know how widely spread the readings are when repeated measurements differ in the result. The spread of values tells something about the uncertainty of a measurement. With it begins the judgement of the quality of the measurement. The usual way to quantify spread is standard deviation. The standard deviation of a set of numbers tells about how different the individual readings typically are from the average of the set.

Uncertainty in a measurement quantity is a result both of the incomplete knowledge of the value of the measured quantity and of the factors influencing it. Such uncertainties can be estimated using statistical analysis of a set of measurements, and using other kinds of information about the measurement process.

There are established rules for how to calculate an overall estimate of uncertainty from these individual pieces of information. The use of good practice, such as traceable calibration, careful calculation, record keeping, and checking, can reduce measurement uncertainties. When the uncertainty in a measurement is evaluated and stated, the fitness for purpose of the measurement can be properly judged [5].

2.1Uncertainty Assessment Steps

The Guide to the Expression of Uncertainty in Measurement (GUM) [6] has developed a framework to assess uncertainty. This research deepens on the standard uncertainty calculation of each uncertainty contributor, -step 3 of the process-, and the different approaches that can be used.

Having defined the measurement process and identified the contributors to the overall uncertainty, the following step is to quantify these sources of uncertainty by convenient means.

Currently, the GUM classifies the sources of uncertainty into A and B, being A the calculation of a standard deviation from a series of repeated measurements and B a judgement exercise using all pertinent information on the possible variability of each contributor. But this is an ambiguous and ineffective classification, and this study facilitates a more efficient and complexity management tailored uncertainty assessment methodology and sources classification.

Figure 2 shows the steps established by GUM needed to calculate the uncertainty, more information regarding this framework can be found in [6].

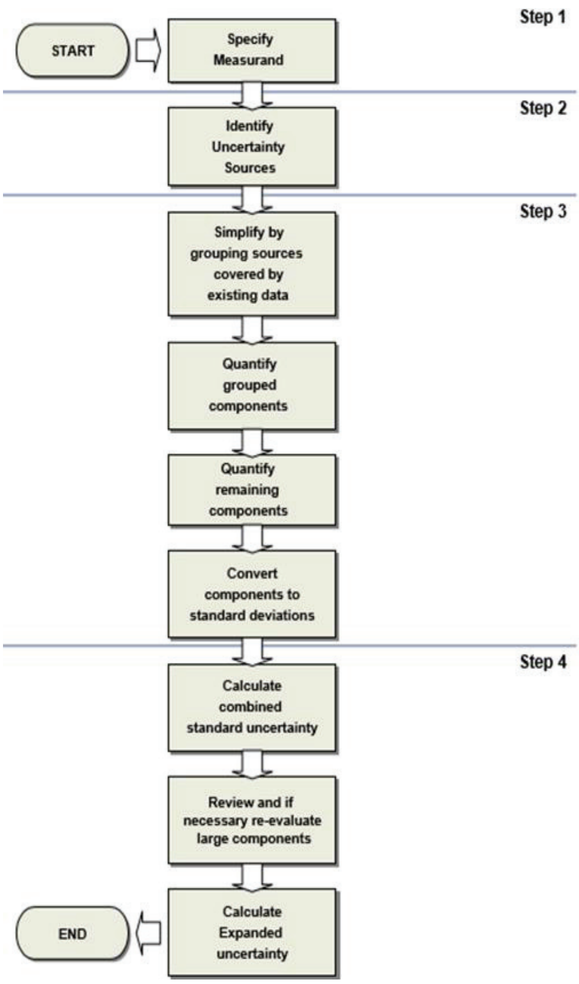

Figure 2: The uncertainty estimation process. Source: [7]

This research intends to give a simplified approach of how aerospace companies should face the calculation of uncertainty when there are different kinds of sources of uncertainty in a measurement process.

On the following chapter, there are given criterion on how to group all sources of uncertainty having a complex measurement process, and then how to quantify the standard uncertainty of each source. Finally, there is given some guidance on how to combine all of them in order to get the measurement process overall uncertainty and how to reduce the uncertainty of the test in an effective way.

3. Uncertainty Assessment Methodology

As explained, measurement processes in the aerospace industry are often complex, and after the identification of sources of uncertainty, assessing the contribution of these sources is usually laborious and difficult.

For each of the contributors, the standard uncertainty and the sensitivity coefficient need to be calculated [8]. Afterwards each source has to be combined in order to calculate the overall uncertainty.

$$u_{overall} = \sqrt{u_1{}^2 c_1{}^2 + u_2{}^2 c_2{}^2 + u_3{}^2 c_3{}^2 + \cdots + u_i{}^2 c_i{}^2} \quad \text{i= nº of sources}$$

$u_{overall}$= combined uncertainty
u_i= standard uncertainty of the ‘i’ source
c_i= sensitivity coefficient of the ‘i’ source

In order to assess the contribution of all sources to the overall uncertainty of a measurement process, different methods can be followed. This research has identified three different means of calculating the standard uncertainty associated to each relevant contributor and proposes a classification of the uncertainty sources based on these three approaches.

For the contributors that have an uncertainty already calculated on the manufacturer specifications or the calibration certificate, this value should be taken for the further calculations.

If there is not any uncertainty assessment stated, and where it is feasible, a model of the uncertainty behavior of the source has to be built, and some estimation carried out.

The rest of contributors should be assessed through statistical analysis, requiring testing.

The identification of every source of uncertainty can be done using the measurement process specialist expertise, literature review, calibration certificates, manufacturer specifications, benchmarking, and some of them are likely to be identified while carrying tests.

After determining the uncertainty contributors, those have to be analysed, and see the information available related to each of them. Depending on the information available, one approach of the three explained earlier has to be chosen.

A combination of different types of information available and the approach that should be used in each case has been collected in Table 1.

Table 1 Uncertainty sources grouping.

Assessment Method	Specifications	Model Based/ Estimation	Statistical Analysis
Existing Calibration Certificate	x	-	-
Existing Manufacturer Uncertainty Statement	x	-	-
Predictable Uncertainty Behavior	-	x	x
Several Measurements Already available	-	-	x
Heavily dependent to other sources	-	-	x
Common Sense Judgement	-	x	-
No information available, difficult to build model	-	-	x

This classification groups the sources into three categories, assessment based on specifications, on mathematical models or estimations, and on statistical analysis.

The uncertainty contributors assessed through specifications are quantified straightforward. The uncertainty value stated by the equipment manufacturer or the calibration certificate needs to be taken. Then, if the distribution has been stated, it has to be used for the further calculation, if not, the recommendation is to use the most conservative one, a rectangular distribution. More information on how to calculate the uncertainty when the manufacturer has already stated it can be found in [9].

If the source is going to be assessed through estimation or building a model of the uncertainty behavior, all assumptions need to be clearly stated, and the measurement process specialist should validate those. It is crucial that the model matches with reality, if not, the third approach should be taken. When there are no available relevant specifications, or creating a model of the uncertainty behavior is too complex or time-consuming, the sources should be assessed by carrying out tests.

This approach should be taken only if the other two are not feasible, as it is time consuming and the effort only compensates if the contribution to the overall uncertainty of the studied source seems to be significant. Once tests have been carried out, the standard uncertainty is calculated using standard statistical analysis. Important is to define the test, and make sure that the test is isolating the studied contributor, only measuring the influence of this source, and it is not influenced by other variables.

Once all standard uncertainties and sensitivity coefficients have been calculated, the combined uncertainty can be determined. Also, the major contributors of the uncertainty are easily identified at this stage, and uncertainty reduction strategy should focus on these key drivers. All sources should be presented against the overall uncertainty, as illustrated in Figure 3.

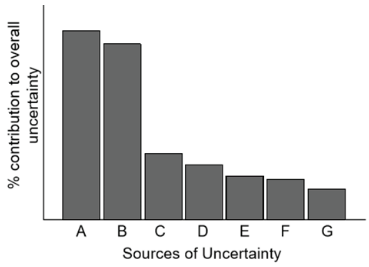

Figure 3: Contribution to the overall uncertainty diagram. Source: Rolls-Royce, 2013.

After assessing all individual uncertainty sources it is important to put together all the information created during the study. The best way to do it is creating the so called UoM budget. This UoM budget collects the following information:

- Uncertainty contributors identified
- Standard Uncertainty
- Sensitivity Coefficient
- Contribution to Overall Uncertainty

The following chapter provides a case study in order to clarify the different approaches that can be used for the standard uncertainty of each source.

4. Industrial Case Study

A case study has been carried out in Rolls-Royce, assessing the uncertainty of the Strain Gauge Calibration Test, for different aerospace components.

First step, as established by the GUM, is the definition of the measurement process, which is shown in Figure 4.

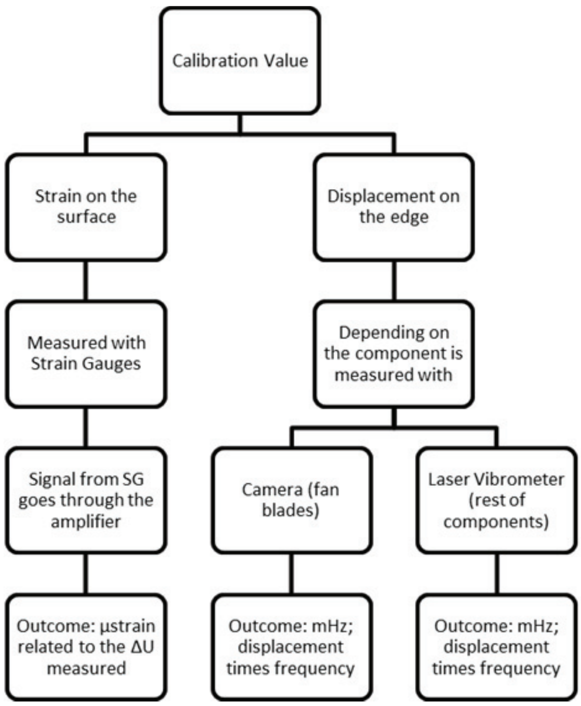

Figure 4: Simplified Strain Gauge Calibration Process

This test consists of measurements of signals from strain gauges which are applied to the component, together with a measurement of displacement at the edge of the component. These two sets of data are combined to produce the so-called strain gauge calibration value. This, in turn, is used to determine component vibrations during aircraft engine run.

Next step corresponds to sources of uncertainty identification. Each step of the measurement process has several uncertainty sources attached. The identification of these contributors was a mix of company expertise, literature review, calibration certificates, manufacturer specifications and testing. Twenty eight uncertainty sources were identified for this specific measurement process. These 28 contributors come from 7 major sources, and their contribution is illustrated in Figure 5.

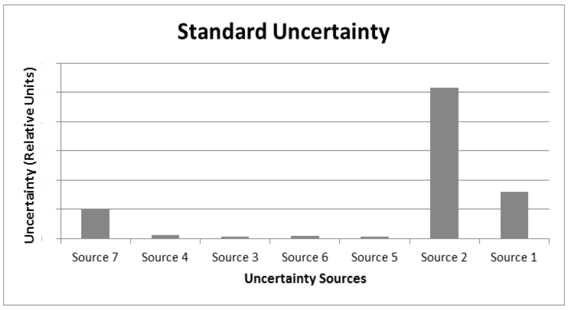

Figure 5: Standard uncertainty of each major source

Following, the source grouping comes. Out of the 28 sources, eight could be calculated based in the specifications approach. Three of them had an uncertainty statement on their calibration certificate and for the other five, the manufacturer had conducted an extensive uncertainty assessment.

Also, eleven of the sources were assessed based on mathematical models. The standard uncertainty of six of them was calculated based on estimations, derived from common sense. For the other five, mathematical models of the uncertainty behavior were developed.

The rest of the sources –nine- were assessed trough statistical analysis, so a test setup had to be built and several tests carried out in order to gather enough information for the estimation of the standard deviation, which is directly related to the standard uncertainty.

The results of each individual assessment were gathered in an UoM budget and the key drivers of the test uncertainty identified.

4.1 Case Study Results

Figure 6 illustrates the seven major sources of uncertainty, and their influence in the overall uncertainty, once all sources have been combined. As the measurement process for fan blades changes with respect to the other components, they have been represented in separated stacks.

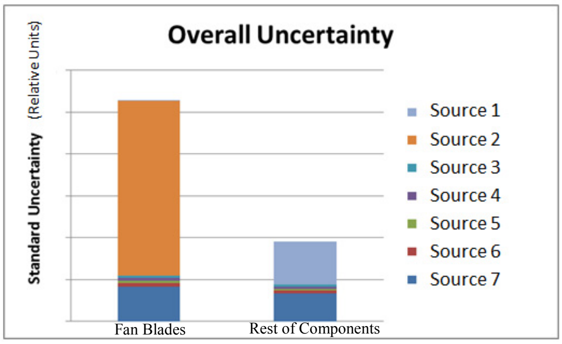

Figure 6: Overall uncertainty of the strain gauge calibration

It can be seen that in the case of strain gauge calibration on fan blades, source 2 is the key driver of uncertainty, so in order to reduce significantly this uncertainty, improvements should be made related to this source.

For the rest of components, source 1 and 7 are the key drivers, so improves should focus on those.

It also can be seen that the uncertainty associated to the strain gauge calibration on fan blades is significantly larger than for the rest of components. That is because this specific measurement process adds a new source of uncertainty which in fact becomes the key driver of this test uncertainty.

In order to reduce effectively the uncertainty of this test, reduction actions should focus first on fan blades strain gauge calibration, specifically in source 2. If the measurement result for the rest of components requires a reduction of uncertainty as well, actions should be taken on sources 3 and 7.

It can be appreciated that currently the measurement process on fan blades has an uncertainty accounting more than double the test for the rest of components, as shown in Figure 7.

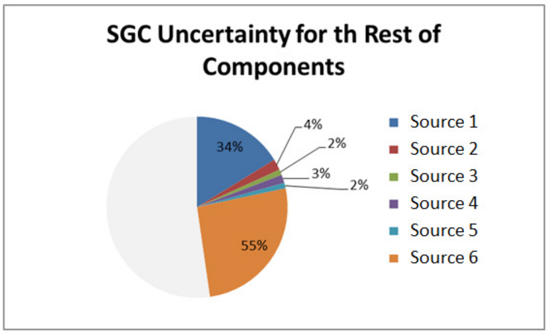

Figure 7: Comparison of the two measurement processes

5. Conclusion and Further Work

In general for any measurement process a huge amount of uncertainty sources can be detected. But normally it is just a few of them that drive a high percentage of the overall measurement uncertainty. Identifying these key drivers of the combined uncertainty is crucial, as these have the maximum improvement potential.

In the specific case of the strain gauge calibration on aerospace engine components, the individual assessment of all the uncertainty contributors already show that some sources actually have a greater influence than others. Once you combine all sources and calculate the overall contribution these influences are more explicit.

Aerospace companies understand the importance of measurement uncertainty and have started quantifying it for their key measurement process. This research clarifies the different approaches that can be taken in the assessment of each uncertainty source, but further work needs to be done in the field of identification of the different sources, as the industry is lacking a standard to do this, relying on the specialists' expertise.

Acknowledgements

The authors would like to thank Cranfield University and Rolls-Royce Plc for the resources provided. This project is supported by Rolls-Royce Deutschland, Dahlewitz.

References

[1] Zhao, Y., Xu, X., Kramer, T., Proctor, F. and Horst, J. (2011), "Dimensional metrology interoperability and standardization in manufacturing systems", Computer Standards and Interfaces, vol. 33, no. 6, pp. 541-555.

[2] Bell, Stepahnie. 1999. A beginner's Guide to Uncertainty of Measurement. Teddington, Middlesex, United Kingdom, TW11 0LW : NPL National Physical Laboratory, 1999.

[3] Désenfant, M and Priel, M. 2006. Road map for measurement uncertainty evaluation. Metrology in Fundamental and Applied Physics, 2006. pp. 841-848 EURACHEM / CITAC. EURACHEM/CITAC Guide CG4 Quantifying Uncertainty in Analytical Measurement. 2000. 63

[4] BIPM, 2008, "Guide to the expression of uncertainty in measurement". Available at: http://www.bipm.org/fr/publications/guides/gum.html (Accessed on 5th of June).

[5] Bell, S. 2001, "A beginner's Guide to Uncertainty of Measurement", Measurement Good Practice Guide No. 11, National Physical Laboratory, Issue 2, pp. 7-8.

[6] Birch, Keith. 2001. Estimating Uncertainties in Testing, Measurement Good Practice Guide No.36. British Measurement and Testing Association. Teddington, Middlesex : HMSO, 2001.

[7] EURACHEM / CITAC. 2000. EURACHEM/CITAC Guide CG4 Quantifying Uncertainty in Analytical Measurement. 2000.

[8] American Association for Laboratory Accreditation, 2014. G104 - Guide for Estimation of Measurement Uncertainty In Testing December.

[9] GUM, 1995. Guide to the expression of uncertainty in measurement, International Organization of Standardization (ISO), Geneva