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ASME MEASUREMENT UNCERTAINTY

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ABSTRACT

The purpose of this paper is to introduce the new ASME measurement uncertainty methodology which is the basis for two new ASME/ANSI standards and the ASME short course of the same name. Some background and history that led to the selection of this methodology are discussed as well as its application in current SAE, ISA, JANNAF, NRC, USAF, NATO and ISO Standards documents and short courses. This ASME methodology is rapidly becoming the national and international standard.

BACKGROUND

The accuracy of test results has always concerned engineers and scientists, but for decades this subject has been plagued by controversy, argument, confusion and even emotion. The absence of an uncertainty calculation standard made significant comparison of test results between facilities, companies and laboratories almost impossible. Still there were good attempts. H. H. Ku of NBS relates the following [1]*:

> "Dan Johnson, an old timer at the Bureau, told me this story. In the 1930's, P. H. Myers at NBS and his colleagues were studying the specific heat of ammonia. After several years of hard work, they finally arrived at a value and reported the result in a paper. Toward the end of the paper, Myers declared:
>
> "We think our reported value is good to one part in 10,000; we are willing to bet our own money at even odds that it is correct to two parts in 10,000; furthermore, if by any chance our value is shown to be in error by more than one part in 1,000, we are prepared to eat our apparatus and drink the ammonia!"

HISTORY

In the research that led to the JANNAF (formerly ICRPG) [2] and the USAF [3] handbooks, a powerful statistical tool, Monte Carlo simulation, was used to select the best methods from the many available. J. Rosenblatt, H. H. Ku and J. M. Cameron of NBS provided excellent constructive criticism of these documents and have continued to support industry in this effort. The references to the NBS publications are particularly recommended to the reader. [1, 4, 5, 6].

By the late seventies, the only major argument that remained was over how to combine the bias error limit with the precision error. Addition of the two components is recommended in [2, 3, 4, 7, 12, 13 and 15]. Combination by the root-sum-square method is recommended in [8, 9, 10, 16, and 18]. This argument could not be solved completely by Monte Carlo simulation as it is largely a matter of opinion. However, these simulations aided significantly in evaluating the statistical characteristics of the two uncertainty intervals. The argument as to how to combine bias and precision errors raged over many committees in several societies, and most participants believed it would never be settled. A compromise was suggested by the NBS group [6] in late 1980. It was suggested that (1) if the bias and precision components are propagated separately from the measurements to the final test result and (2) the method of combination is clearly stated, then either the addition or root-sum-square method should be accepted as it is the last step in the calculation and can easily be undone. Shortly thereafter, the ASME, SAE and ISA committees approved this compromise of allowing the analyst to decide and state which uncertainty model (ADD or RSS) was to be used.

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* Numbers in brackets designate references at the end of this paper.

CURRENT ACTIVITIES

1. ASME. The two ASME committees are:

   ANSI/ASME PTC 19.1 - 1983 - Measurement Uncertainty -
   ANSI/ASME MFC-2M-1983 - Uncertainties in Flow Measurement -

   In addition, the ASME Short Course on Measuring Uncertainty is scheduled for the 1983 ASME-WAM.

   The status of these ANSI/ASME documents is described in later sections of this paper.

2. SAE. Committee E33 on "Aircraft In-Flight Propulsion Measurement and Uncertainty," is drafting an SAE Aerospace Information Report (AIR 1678) titled, In-Flight Thrust Measurement Uncertainty, which they hope to distribute for industry review in 1984. This document uses the same uncertainty methodology as that of this paper. The activities of this committee are described in [11].

3. ISA. The Instrument Society of America provides a short course titled, Test Measurement Accuracy, at the International Instrumentation Symposium and other locations several times a year. This course is identical to the ASME Short Course. ISA also has formed a Measurement Uncertainty Committee to encourage and promote the use of measurement uncertainty analysis. The United States Air Force Handbook [3] has been reprinted as the ISA Measurement Uncertainty Handbook [13].

4. ISO. ISO TC30 SC9 approved the method described herein at their meeting in Leningrad in May 1982 and requested a revision of the existing world standard ISO 5168 [11]. The second draft was reviewed at their recent meeting in Washington, D. C. at the National Bureau of Standards in November 1982.

5. MIDAP. The British Ministry Industry Drag Analysis Panel published their report, Agardograph 237, in 1979 [10]. In a joint meeting held with SAE Committee E33 in England in May 1982, the uncertainty methodology was coordinated between these two groups.

6. ASQC. The ANSI Committee Z11 has commissioned an ASQC Writing Group on Calibration Assurance. This Writing Group is drafting a national standard on assuring the quality of calibration [15]. Although this standard treats only calibration error, it is consistent with the methodology recommended herein.

7. NRC. At the Idaho National Engineering Laboratory, a report titled, Semiscale Uncertainty Report: Methodology [14], has been written for the United States Nuclear Regulatory Commission. This document uses the uncertainty methodology described herein. Nuclear Material Control, Mass Calibration Techniques, ANSI N15.18-1975, also is consistent with the recommended methodology.

8. NATO. NATO AGARD PEP 15 Committee on Uniform Engine Testing is conducting an interfacility test of two jet engines at NASA-LEWIS, USAF AEDC, USN NAPC, Britain's NGTE, France's SACLAY facility and a Turkish facility. This committee, selected the recommended uncertainty methodology as their standard for this program at their meeting in Toulouse, France in May 1981.

9. CRC. The Coordinating Research Council has decided to re-evaluate the test data from their Atlantic City test program on engine exhaust emissions using the recommended uncertainty methodology.

BRIEF DESCRIPTION OF METHODOLOGY

Measurement Error

It is a well-accepted principle in engineering that all measurements have errors (δ_k). These errors are the differences between the measurements and the true value (see Figure 1). Furthermore, the total error is usually expressed in terms of two components: a fixed (bias) error (β), and a random (precision) error (ε_k) such that

$$\delta_k = \beta + \varepsilon_k \quad . \tag{1}$$

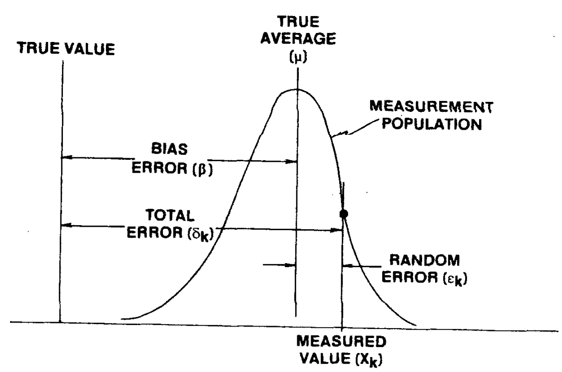

Figure 1
MEASUREMENT ERROR

Precision Index

The precision error is determined by taking N repeated measurements from the parameter population, the characteristics of which can be approximated by the precision index (S) defined by the familiar

$$S = \left[\frac{\sum_{k=1}^{N} (X_k - \bar{X})^2}{N-1} \right]^{1/2} \quad . \qquad (2)$$

where $\bar{X}$ is the average value of X.

The precision index of the average of a set of measurements is always less than that of an individual measurement according to

$$S_{\bar{X}} = \frac{S}{\sqrt{N}} \quad . \qquad (3)$$

Bias Error

The bias error is the systematic error which is considered to remain constant during a given test. Thus, in repeated measurements of a given set, each measurement has the same bias. There is no statistical equation, as (2) or (3), to define the bias limit, B. Instead, it must be estimated, and this is not an easy matter since the true value is not known. Calibrations help, as does a comparison of measurements by independent methods, but in general the estimate of bias must be based on judgment.

Combining Errors

Errors arise from many sources. These are divided arbitrarily into three categories: calibration errors, data acquisition errors, and data reduction errors. For each of these sources of error there will be bias and precision components.

To obtain the precision of a given parameter (like temperature, pressure, or flow rate), the root sum square (RSS) method is used to combine the precision indices from the K sources of error. Thus

$$S = [S_1^2 + S_2^2 + \ldots + S_K^2]^{1/2} \quad . \qquad (4)$$

Similarly, the bias of a given parameter is given by

$$B = [B_1^2 + B_2^2 + \ldots + B_K^2]^{1/2} \quad . \qquad (5)$$

Uncertainty of a Parameter

If a single number (U) is needed to express a reasonable limit of error for a given parameter, then some model for combining the bias and precision errors must be adopted, where the interval

$$\bar{X} \pm U \qquad (6)$$

represents a band within which the true value of the parameter is expected to lie, for a specified coverage.

While no rigorous confidence level can be associated with the uncertainty (U), coverages analogous to the 95% and 99% confidence levels can be given for the two recommended uncertainty models. Thus

$$U_{ADD} = B + t S_{\bar{X}} \text{ provides} \approx 99\% \text{ coverage,} \qquad (7)$$

$$\text{and } U_{RSS} = [B^2 + (tS_{\bar{X}})^2]^{1/2} \text{ provides} \approx 95\% \text{ coverage.} \qquad (8)$$

The Student t value is a function of the degrees of freedom (ν) used in calculating $S_{\bar{X}}$. For large samples, (i.e., N>30), t is set equal to 2, otherwise the Welch-Satterthwaite formula is used to provide ν, according to

$$\nu = \frac{\left(\sum_{j=1}^{3} \sum_{i=1}^{K} \frac{S_{ij}^2}{N} \right)^2}{\sum_{j=1}^{3} \sum_{i=1}^{K} \frac{S_{ij}^4}{N^2 \nu_{ij}}} \quad . \qquad (9)$$

where S_{ij} represents the precision indices of the various error sources involved, and ν_{ij} represents the degrees of freedom of these same error sources.

Uncertainty of a Result

Errors in measurements of various parameters (P) are propagated into a derived result (r) through the functional relationship between the result and its independent parameters. The relationship provides the sensitivity factors (θ_i), which indicate the error propagated to the result because of unit error in the parameter. Thus if

$$r = f(P_1, P_2 \ldots . P_J) \qquad (10)$$

where J is the number of parameters involved,

then

$$\theta_i = \frac{\partial r}{\partial P_i} \quad . \qquad (11)$$

The bias and precision errors of the parameters are kept separate until the last step of computing the uncertainty of a result. Thus, the precision index of a result is given by

$$S_r = \left[\sum_{i=1}^{J} (\theta_i \, S_{P_i})^2 \right]^{1/2} \tag{12}$$

and the bias limit of a result is given by

$$B_r = \left[\sum_{i=1}^{J} (\theta_i \; B_{P_i})^2 \right]^{1/2} . \tag{13}$$

The uncertainty of a result is again given by the two models according to

$$U_{r_{ADD}} = B_r + tS_r \quad @ \; 99\% \tag{14}$$

and

$$U_{r_{RSS}} = \left[B_r^{\;2} + (tS_r)^2 \right]^{1/2} \quad @ \; 95\% . \tag{15}$$

The Student t value is a function of the degrees of freedom used in calculating S_r. For large samples of all parameters, (i.e., N>30), t is set equal to 2, otherwise the Welch-Satterthwaite formula is used to provide ν_r according to

$$\nu_r = \frac{S_r^4}{\sum_{i=1}^{J} \frac{(\theta_i \, S_{P_i})^4}{\nu_{P_i}}} . \tag{16}$$

ASME PTC 19.1, MEASUREMENT UNCERTAINTY

This committee was formed in 1979 to provide the Performance Test Codes Board with an authoritative Supplement on which to base Measurement Uncertainty Analyses. This was for the use of the various Code and Supplement writing committees.

This committee has endorsed and contributed to the methodology of this paper, and has just completed a draft for the PTC Board and Industry approval [16].

The document includes a nomenclature and a glossary of terms that are in agreement with the various International Standards. A detailed review of the methods of this paper is included, as is a strong section on Applied Considerations. This latter includes: multiple test uncertainty, long versus short term tests, comparative versus absolute tests, spacial variations, outlier treatment, regression uncertainty, weighting method, pre- and post-test analyses, and number of measurements required. A step-by-step calculation procedure is given, as well as worked-out examples applying the method.

All in all, we expect to satisfy the PTC requirements for an authoritative document on measurement uncertainty that is easily understood and applied.

ASME MFC, FLUID FLOW MEASUREMENT UNCERTAINTY

The ASME Standards Committee on the Measurement of Fluid Flow in Closed Conduits (MFC) was formed in 1973 as a result of the recognition by those actively working in the field that there was a need for a single national standard on this subject. In most Western European countries, national standards on flow measurement have been in use for many years. These are usually promulgated by government supported agencies such as the British Standards Institute in the United Kingdom, AFNOR in France, VDI in West Germany etc. The first International Standard on Flow Measurement ISO/R541 was published in January 1967.

This country has had no national standard, but many authoritative documents on flow measurement existed such as the ASME Report "Fluid Meters, Their Theory and Application" [17], PTC 19.5 on Flow Measurement, AGA Report #3 on Gas Flow Measurement, etc. For the most part, these documents were in agreement on their methodology, coefficient values, required upstream lengths, and calculation procedures.

This was not true on the international scene, and the initial ISO document contained many compromises between USA procedures and those in use throughout Western Europe. Differences in required upstream lengths and coefficient values have not yet been resolved.

All of these publications, those within the USA, the European national standards, and the international standards, address the question of the accuracy of a flow measurement. However, each document created its own procedures for estimating the uncertainty and values given were based on human judgment usually biased by the individuals involved.

The first publication of a standard devoted entirely to the estimation of uncertainty of a flow rate measurement was ISO/DIS 5168 published in 1976.

Recognizing the importance of this subject matter, the ASME Standards Committee MFC set up its first subcommittee, i.e., SC1 with the charge to prepare a USA standard on Uncertainties in Flow Measurement. It has taken many years, 10 to be exact, and much effort by the people involved, to produce the first ANSI/ASME MFC - 2M Standard on Uncertainties in Flow Measurement which was published in 1983 [18]. The methodology follows that of the preceding section of this paper and should form the basis of some further, more applied, or working documents on flow measurement.

SUMMARY

Engineering judgment and experience is still required when estimating bias or systematic errors but this is clearly stated in [18] and all parties to a contract can agree beforehand to the values that should be used.

Unfortunately we are still left with many unanswered questions that must be resolved in the not-too-distant future. For instance: How do we interpret statements by the manufacturers of industrial instrumentation that claim a device to be "accurate to within ±0.5% of full scale"? That is: How much of this is bias error and how much should be attributed to random or precision error? Similarly, when dealing with meter coefficients: How do we interpret values given in [17] for the 2σ tolerance on the discharge coefficient? It is necessary that the concepts of this paper be adopted throughout all segments of industry and one day we will have a uniform, unambiguous method of estimating the uncertainty of not only a flow measurement, but measurements of all kinds.

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