TEST UNCERTAINTY RATIO (TUR) AND TEST UNCERTAINTY

by

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ABSTRACT

SAMIRA KHANAM. Test uncertainty ratio (TUR) and test uncertainty. (Under the direction of DR. EDWARD MORSE)

Measurement uncertainty is a natural parameter that can be used to characterize any measurement process. Continually increasing demands of higher and higher dimensional accuracy in manufactured components places similar demands on the field of dimensional measurement, as manufacturers strive for lower uncertainty associated with the results of measurement. Complete elimination of uncertainty in manufacturing and measurement is not the intent of this research, as only the reduction of uncertainty is possible, and the reduction of uncertainty comes at a cost. Given that similar manufacturing and measurement equipment is available across industries, it is often the case that the better one can estimate these uncertainties, the greater the competitive advantage as money to reduce uncertainty – thereby improving quality – can be used in the most effective way. The objective of this research is to analyze the impact of two different kinds of uncertainty – the "Test Uncertainty Ratio" and "Test Uncertainty" – for both manufacturers of measurement equipment and their customers. This impact influenced both by their understanding of what the uncertainty represents, as well as their ability to characterize this uncertainty.

Measuring equipment often has a stated 'accuracy' within which it can be expected to perform. However, some complex measurements performed with this equipment have additional uncertainty contributors, and the resulting measurement is less accurate (i.e. has a greater uncertainty) than the instrument's stated performance. The Test Uncertainty Ratio (TUR) for a measuring process is one of a family of metrics that relate the tolerance for a measurand to the uncertainty present in performing that measurement. This ratio is used in industry to describe the measurement capability of a system or process, but often is not based on a realistic estimation of the uncertainty present. This research clarifies the uncertainty contributors for the calculation of this metric, and experimentally validates different estimation techniques. It is common to perform a test of the instrument on an artifact with known dimensions, when buying and selling metrology tools. The errors obtained during this test are used to evaluate the instrument, but the errors will reflect not only instrument deficiencies, but also improper use of the instrument, and incomplete knowledge of the test artifact. The contributors to the errors in this type of test that are not associated with the instrument itself have been lumped into a term called Test Uncertainty. This is a new concept, and is receiving much attention in both the accreditation of metrology laboratories and in national and international standards writing bodies. This research in the area of test uncertainty develops a consistent way of considering test uncertainty and its influence in the evaluation of measuring instruments. Experimental results support the method of decomposing uncertainty contributors into those that do and do not affect the test uncertainty.

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CHAPTER 1: INTRODUCTION

The history of measurement processes is comprised of scientific advancements. To improve the quality of the products, measurements have a significant role in many business sectors, especially in the manufacturing industries. In the evaluation process of manufactured products, measurement systems play a key role. The acceptability of the measurement systems depends on their ability to produce accurate measurement results. The measurement results need to verify that products meet the expected quality levels for both for the suppliers and the customers. Each measurement contains errors due to the limits of instruments and the people using them. Different methods have been developed to estimate the measurement errors that may occur. One of these methods is the use of measurement uncertainty. Measurement uncertainty is a description of the collection of all possible measurement errors [4]. A measurement result can only be complete when it is expressed with a statement of its uncertainty. The quality of a measurement result is reflected in its uncertainty with reference to its value and its traceability to the international systems units through various national and international standards [2].

The uncertainty of measurement results is a key concern to both industries and their customers. Measurement results can be used in decision making when the data are analyzed with uncertainty. The uncertainty statement is important in manufacturing industries, as well as testing and calibration laboratories, not only for acceptability of part and processes but also to reduce the cost. The accuracy of measurements, characterized by uncertainty, affects all of us in trade.

1.1 Measurement Uncertainty

The measurement process is complicated by the presence of intrinsic variations which affect the measurement results. Consequently, measurement results will always contain errors. This error is defined as the difference between the measurement result and the true value of the quantity being measured. In practice, no one can know the true value, so a test of a measuring system compares the measured value to a reference value. The reference value and its uncertainty are accepted as valid to evaluate a measuring system. If calibrated at NIST (National Institute of Standards and Technology) or another recognized national metrology institute, the true value is accepted to be that reference value, within the stated uncertainty. Measurement Uncertainty is defined as "the parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand" [3]. The term measurand is defined as the quantity subject to a measurement. One widely accepted method to calculate uncertainty is defined in "Guide to expression of Uncertainty in Measurement" [5], or GUM. The first step is to identify the sources of errors (the contributors) of uncertainty. These contributors include the environment, the measurement equipment, the measuring procedure, measurement set-up, and even the metrologist performing the measurement. After finding all relevant sources of uncertainty, it is necessary to calculate a standard uncertainty for each individual source. There are two types of evaluation of standard uncertainty: Type A – which is evaluated by statistical means and Type B – which is evaluated by methods other than statistics.

The next step is to work out combined uncertainty, which – for independent contributors – is the root sum square of individual uncertainty terms. Finally, the expanded uncertainty is calculated using an appropriate coverage factor. The expanded uncertainty can be thought of as a confidence interval within which the true is expected to lie. Estimating measurement uncertainty is explained in detail in chapter 2. This dissertation examines the application of measurement uncertainty in two different contexts: determining the suitability of a measuring process for a given task, and determining the quality of test method and test method for evaluating a measuring instrument.

1.2 Test Uncertainty Ratio (TUR)

Measurement equipment performs an essential task in the production process. Presently, the quality of the product is the main concern for manufacturing industries. The increase in the expectation of the quality of the products drives designers to utilize tighter tolerances, and as a result the products acceptance criteria become inflexible. Different powerful methods have been developed in the industry to verify the acceptance of the product such as Gage R&R and to find the measurement capability of the measurement equipment such as P/T. One such method analyzed in this research is the Test Uncertainty Ratio (TUR). It helps to verify that the acceptance of the manufactured product is reliable, and also to find the measurement capability of measurement equipment. In its most simple form, TUR is the ratio between the tolerance for a specific measurand and the uncertainty in determining the measured value for that measurand. This ratio has the specified tolerance in the numerator, and the uncertainty in the denominator. Currently, a ratio of 4:1 or even 3:1 is considered acceptable. The higher value of the ratio indicates the better the performance of the test. To calculate TUR one needs to know tolerance and the uncertainty. Tolerances appear in the manufacturer's product specification. The other term, uncertainty, is the main concern to calculate TUR. To provide a meaningful TUR, the uncertainty must be evaluated for each specific task in a specific measurement plan. There is no single value that is appropriate for every measuring task performed by a given instrument. The TUR needs to be calculated for each task separately. This approach to the Test Uncertainty Ratio is explained in detail in chapter 5.

1.3 Test Uncertainty

Test uncertainty is a new concept in the field of evaluating measurement processes. When one is testing a piece of equipment, the uncertainty during that test is known as test uncertainty. When calibrating instruments, some common sources of errors are the measurement equipment itself, the person who is doing the test (the tester), and the artifact from which the reference value is obtained. As the instrument is being calibrated, the error from the instrument itself is not included in test uncertainty. The test uncertainty captures the ability of the test to evaluate the instrument, so its value is smaller than the regular measurement uncertainty that occurs when the instrument is used to measure work pieces. When calibrating the instrument, the uncertainty due to the artifact and the tester are primary contributors to the test uncertainty. The research in this dissertation has revealed that the artifact uncertainty is usually does not influence the test uncertainty on a large scale. Influences that fall under the tester's responsibility, including the performance of the tester when doing the test, has great influence on the calibration results. So test uncertainty result varies with the performance of the human operator (tester). The effectiveness of the test can be increased by increasing the performance of the tester; consequently test uncertainty value will be decreased. Test uncertainty does not indicate the instrument's performance; it is only the indication of the quality of the test. Test uncertainty explained in detail in chapter 6.

1.4 Objective of this research

The lack of industrial knowledge and understanding concerning the use of measurement capability analysis for metrology tools, and also the need for guidance in classifying the different kinds of uncertainty present in the testing and calibration of instruments are the main motivation behind this project.

The goals of this project are

- To develop a guideline on how to use TUR in industry, both to find the measurement capability of measuring instruments and in the inspection of manufactured products.
- To provide a useful uncertainty model that supports decision rules for instrument test criteria, facilitating the buying and selling of metrology equipment, and in equipment calibration.
- To support B89 and ISO Standards activity, and the NCSLI dimensional committee. New efforts are underway in each group studying test uncertainty.

This thesis develops a method for using TUR which will help industries to evaluate measurement equipments' capability, to do comparisons of the capabilities between measurement equipment, and also to check the acceptability of the end products. Next, this thesis provides a model to explain test uncertainty in a way that is consistent with existing view of uncertainty. This work will assist different standard groups, and give a guideline to better understanding of using specifications in the buying and selling of measurement equipment.

It will provide a consistent vocabulary for terms and definitions related to uncertainty, as well as computer simulations and experimental measurements on actual measuring equipment and compare to these estimates to support the goal. It will also assist users of metrology equipment by giving a clear understanding of the relationship between precision, accuracy, repeatability, reproducibility and total variability in the measurements. It will also provide a platform to evaluate the task specific uncertainty not only for simple measurements, but also for the complex measurements performed using a coordinate measuring machine (CMM). Different part positions, fitting algorithms, sampling strategy can be use to evaluate task specific uncertainty. Theoretical methods that are used include simulation software (PUNDIT, commercial software to evaluate uncertainty for CMMs) and MATLAB (Mathematics software) programs for this evaluation. Practical measurement experiments have been done using a CMM with PC-DMIS software.

CHAPTER 2: MEASUREMENT UNCERTAINTY

Measurement is the process or set of operations to assign the value of particular quantity. The assigned value is called the measurement result which describe the quantity which is measured. It is the charactaristics of an object like the size, position, length. In the Measurement system analysis reference manual, a measurement system defined as "the collection of operations, procedures, gages, and other equipment, software and personnel used to assign a number to the characteristics being measured; the complete process used to obtain a measurement."

Measurand need to define first for the measurement process. A measurand is a specific quantity subject to measurement. To define the measurand one should consider the factors which influence the measurement process and expected accuracy of measurement result.Some examples:

- The temperature is an important information in defining the measurand when the length of iron bar is measured in micron level accuracy. The measurand in this case can be defined as the length of iron bar at 20^0 C.
- The tension of the rope need to define when measurand is the length of a rope because it affects the measured length of the rope.
- For the calibration of dial gages and calipers if the measurand is the length of gage block used as a reference standard the temperature at which the

measurement is to be done is important information. The measurand in this case can be defined as the length of gage block 30^0 C and 50% relative himidity. [2]

So the measurand is a attribute which need to define and it is important to mention the environmental condition under which measurement proceeded.

Measurement result is the out put of the measurement process or can be define as numerical value of the measurand. The output result for an ideal and perfect measurement system can be define as true value of the measurand. In this case repeat observations will consistently give exactly same result, so there would be no error. But in reality this does not exist. So the measurement results are compared with reference value which can be known from measurement standard. This is not the exactly true value but close to true value. Many factors influence the result of the process like measurement equipment, environment, skill of the person who is doing the measurement etc. These factors influence in the variations in the measurement result and consequently measurement results always associated with error. Error is the difference between the true value and the measurment result. True value as mentioned can never be known. So it is a qualatative concept, can not be quantified . Repeat measurement is also important for the reliability of the measurement results. One can not make decision only depend on a single measurement result. So measurement results introduce uncertainty in the measurement process which can be quantified. The estimated interval, which quatifies the " how good or how bad" part of the measurement result , is called measurement uncertainty[2]. It can be express as an interval between two values within minimum and maximum values. The true value is expected in this range. For example a measurement result is 20.00 with the uncertainty interval 19.90 to 20.20. The range of the interval is 0.20. It can be define as

20.00 ± 0.20. So measurement results can be characterized by measurement uncertainty. The uncertainty in measurements should be small enough that the measurements meet the specifications needs for which they are made[2].

FIGURE 1 is showing the difference between error and uncertainty.

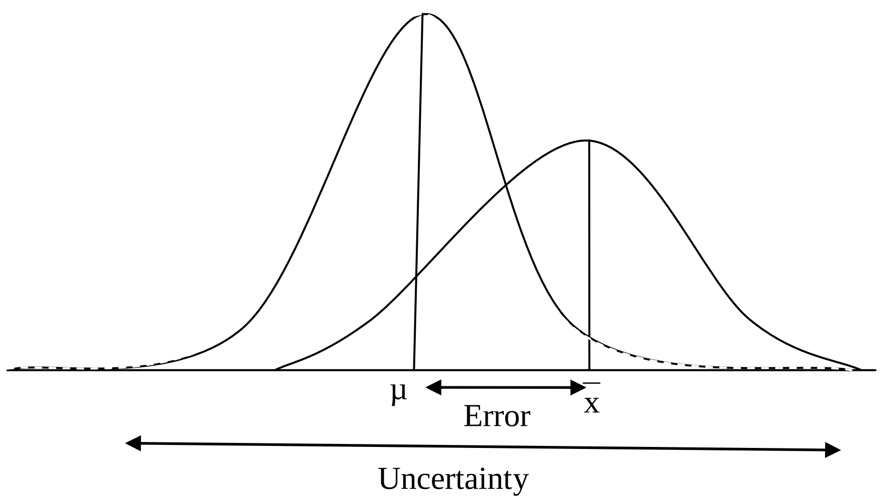


FIGURE 1: Graphical representation of error and uncertainty [2]

It is essential to analyze the measurement steps to find the resons for variations in measurement results and taking actions accordingly to lessen the unceratinty value. Statistical analysis of the measurement results are used to evaluate uncertainty.

2.1 Uncertainty Contributors

Any component that affects the result of a measurement is considered as an uncertainty contributors. Some of the most common contributors are shown in FIGURE 2 from ISO 14253-2.

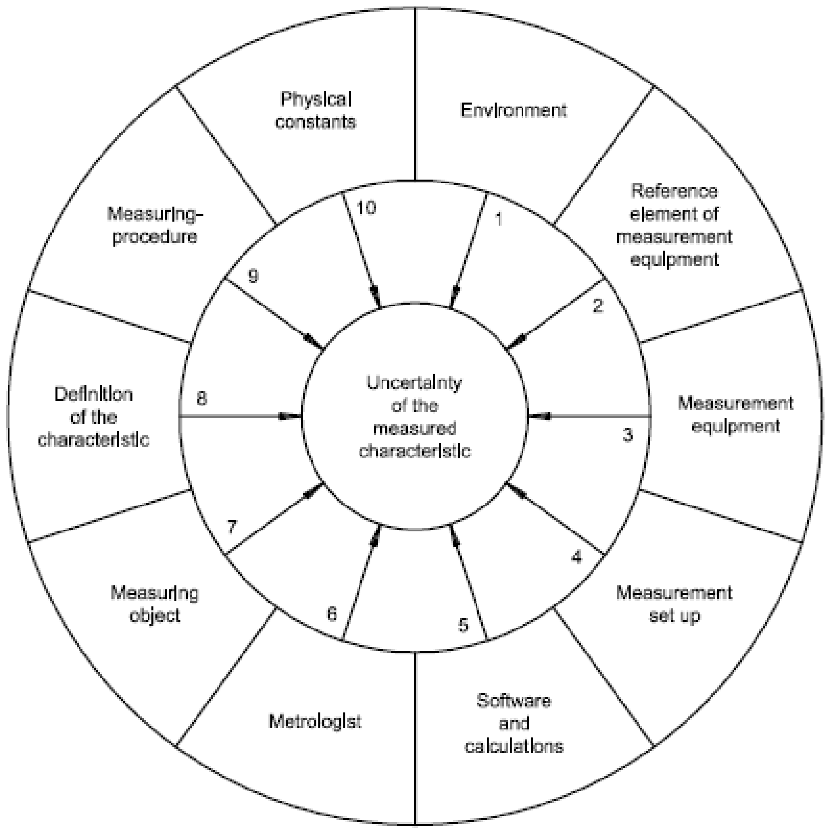


FIGURE 2: Uncertainty Contributors in measurement

From ISO-14253-2 the contributors are described below.

1. Environment for the measurement

The measurement process is influenced by the environment conditions like temperature of the room, part, time variations in measurement steps, humidity of the room. Temperature is the main contributor of the environment. It may influence both the measurement process and measurand. When measuring the length of a block the temperature variation may effect on the result of measurand.The environment is also influenced by the vibration of the measurement tool or object where it is placed, heat radiation, air flow, instrument thermal equivalent.

2. Reference element of measurement equipment

The measurement process is influenced by the reference element of measuring equipment like stability, scale mark quality, temperature expansion coefficient, resolution of the main scale (analogue or digital). When measuring the diameter of a cylinder because of the resolution or stablity of measuring equipment it may effect on the result of measurand. Some other factors like physical principle: line scale, optical digital scale, spindle, rack and pinoion, interferometer, CCD-techniques,uncertainty of the calibration, time since calibration may contributors of measurement uncertainty.

3. Measuring Equipment

The measurement process is influenced by measuring equipment like magnification, electrical or mechanical, error wavelength, zero-point stability, force stability/ absolute force, probe system, geometrical imperfections, stiffness/rigidity, temperature stability/sensitivity, parallaxes, time since last calibration, digitization.

4. Measurement Setup (excluding the placement and clamping of the workpiece)

Measurement setup like cosine and sine errors, temperature sensetivity, stiffness/rigidity, Abbe principle, tip radius, form deviation of tip, interaction between workpiece and setup influence in the measurement procedure.

5. Software and Calculations

Measurand and measurement process are influenced by rounding/quantification, algorithms, implementation of algorithms, number of significant digits in the computation, sampling, filtering.

6. Metrologist

The performane of the metrologist one of the important source of uncertainty. The quality of the metrologist like education, experience, training, physical disadvantage/ability, knowledge, honesty, dedication all may influence to measurement result.

7. Measuring Object, workpiece or measuring instrument characteristic

Charateristics of measuring object, workpiece, measuring instrument like surface roughness, form deviations, temperature expansion coefficient, conductivity, weight, size, shape, cleanliness, workpiece distrotion due to clamping, orientation may influence in the measurment procedure. When measuring diameter of a ball if the surface is rough it will effect on the result of the measurand.

8. Definition of the GPS characteristic, workpiece or measuring instrument characteristics

Datum, reference system, degrees of freedom, toleranced feature, distance, angle these characteristics are also contributors of uncertainty.

9. Measuring Procedure

Number of measurements, duration of measurements, alignment, choise of apparatus, choise of metrologist, number of operators, strategy, clamping, fixturing, numper of points, probing principle and strategy, alignment of probing system, drift check, reversal measirements, error seperation all the factors may contributor of uncertainty. For example if number of measurement is more the result may reflect more reliability.

Physical Constants and conversion factors, material properties of the workpiece, measuring instrument etc. also influence the measurement procedure.

2.2 Definitions

To Understand Measurement Uncertainty, it is necessary to understand some terms in details. These are explained from the International Vocabulary of Basic and General Terms in Metrology (VIM) and the Guide to Expression of Uncertainty in Measurement (GUM).

Measurement

> Measurement is a process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity.

Measurement does not apply to nominal properties. It implies comparison of quantities and includes counting of entities. It presupposes a description of the quantity commensurate with the intended use of a measurement result, a measurement procedure, and a calibrated measuring system operating according to the specified measurement procedure, including the measurement conditions.

Measurand

> Quantity intended to be measured.

The specification of a measurand requires knowledge of the kind of quantity, description of the state of the phenomenon, body, or substance carrying the quantity, including any relevant component, and the chemical entities involved.

Measurement method

> Measurement method describes generic description of a logical organization of operations used in a measurement.

Measurement methods may be qualified in various ways such as:

— Direct measurement method, and

— Indirect measurement method.

Measurement procedure

> Detailed description of a measurement according to one or more measurement principles and to a given measurement method, based on a measurement model and including any calculation to obtain a measurement result.

A measurement procedure is usually documented in sufficient detail to enable an operator to perform a measurement.

Measurement result

> Result of measurement can be defined as a set of quantity values being attributed to a measurand together with any other available relevant information.

A measurement result generally contains "relevant information" about the set of quantity values, such that some may be more representative of the measurand than others. This may be expressed in the form of a probability density function (PDF). A measurement result is generally expressed as a single measured quantity value and a measurement uncertainty. If the measurement uncertainty is considered to be negligible for some purpose, the measurement result may be expressed as a single measured quantity value. In many fields, this is the common way of expressing a measurement result.

True quantity value (True value)

> True value of a quantity is true value.

It is consistent with the definition of a quantity. In the error approach to describing measurement, a true quantity value is considered unique and, in practice, unknowable. The uncertainty approach is to recognize that, owing to the inherently incomplete amount of detail in the definition of a quantity, there is not a single true quantity value but rather a set of true quantity values consistent with the definition. However, this set of values is in principle and in practice, unknowable. Other approaches dispense altogether with the concept of true quantity value and rely on the concept of metrological compatibility of measurement results for assessing their validity.

Measurement error (Error of measurement)

Error is a measured quantity value minus a reference quantity value.

The concept of ‘measurement error’ can be used both when there is a single reference quantity value to refer to, which occurs if a calibration is made by means of a measurement standard with a measured quantity value having a negligible measurement uncertainty or if a conventional quantity value is given, in which case the measurement error is known, and if a measurand is supposed to be represented by a unique true quantity value or a set of true quantity values of negligible range, in which case the measurement error is not known.

Measurement uncertainty

> Uncertainty non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used.

Measurement uncertainty includes components arising from systematic effects, such as components associated with corrections and the assigned quantity values of measurement standards, as well as the definitional uncertainty. Sometimes estimated systematic effects are not corrected for but, instead, associated measurement uncertainty components are incorporated. The parameter may be, for example, a standard deviation called standard measurement uncertainty (or a specified multiple of it), or the half-width of an interval, having a stated coverage probability. In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.

Standard Uncertainty (u_i)

The representation of each component of uncertainty that contributes to the uncertainty of measurement, by an estimated standard deviation is termed as standard uncertainty.

Combined Standard Uncertainty (u_c)

The combination of all the standard uncertainties, which represents the standard deviation of the result, is known as combined standard uncertainty.

It is usually the square root of the sum of the squares of the individual standard uncertainties.

Expanded Uncertainty (U)

The combined standard uncertainty times the coverage factor gives the expanded uncertainty.

The expanded uncertainty forms a boundary about the measurement result y within which the measurand Y is confidently believed to lie.

$$y - U \le Y \le y + U$$
$$or$$
$$Y = y \pm U$$

Coverage factor (k)

A number larger than one by which a combined standard measurement uncertainty is multiplied to obtain an expanded measurement uncertainty.

Evaluation of measurement uncertainty

According to GUM the first step to evaluate measurement uncertainty is to find the sources of errors which are the part of the measurement results. They are shown in

FIGURE 3.

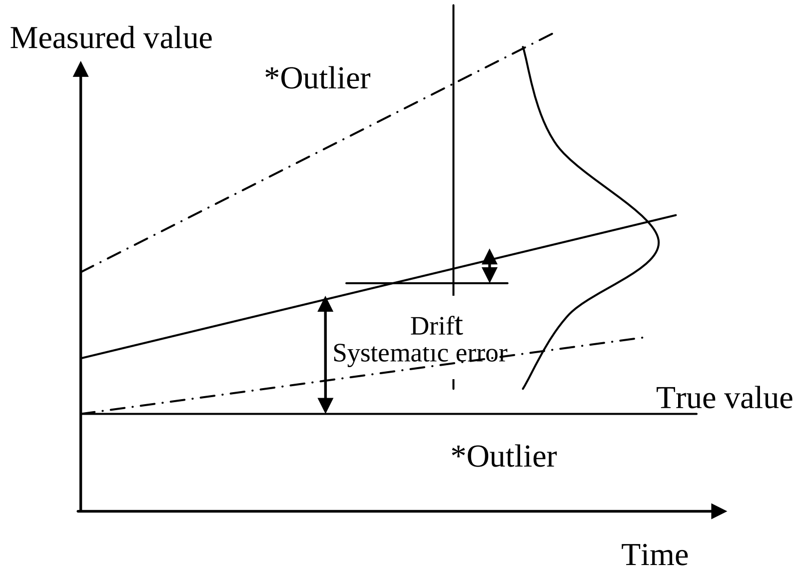


FIGURE 3: Sources of errors [1]

Random Errors

It arises from random flactuation in measurement which cannot be predicted.

It cannot be completely eliminated, but can be lessen by doing the measurement many times. It may be espressed by the standard deviation and the type of distribution.

Systematic Errors

It arises from recognizable effects, which are expected in the measurement system and can be corrected for in advance.

It may be characterized by size and sign (+ or -). It can not be completely eleminated, but it can be analyzed by calibration.

Drift

It is often an effect of time and wear .

It may be expressed by change per unit time or per amount of use. It can be reduced by knowing the influencing factors.

Outliers

These are caused by non-repeatable incidents in measurement system.

These are very difficult (almost impossible) to characterize in advance. Any non repeatable causes like electrical disturbaces, mechanical effects, noise all of these can be the examples of outliers.

Evaluation of standard uncertainty ($u(x_i)$)

The measurand can be the result of a single measurement. So it can be measured directly or it can be determined from other quantities through a functional relationship. It most cases this relationship is used.

$$Y = f(X_1, X_2, \ldots\ldots, X_N)$$

Where X_1, X_2 are determined either by direct measurement or by evaluating certain functions. These quantities may be independent of each other or correlated. The f can be determined from prior knowledge about the nature of behavior of quantities involved, use of numerical evaluation and experiment [7].

Type A evaluation of measurement uncertainty

Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by standard deviations.

The estimation of uncertainty through type A can be done in any one of the following ways.

- Estimating the standard deviation of the data set.
- Adopting the method of least squares to fit a curve representing the data and deriving parameters from the fit.

- Using the analysis of variance (ANOVA) to estimate uncertainty.

Type B evaluation of measurement uncertainty

The other components, which may be evaluated by Type B evaluation of measurement uncertainty, can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information, other than a Type A evaluation of measurement uncertainty. Type B can be determined by

- Techniques other than statistics are used to evaluate standard uncertainty.
- Usually evaluated by scientific judgment based on available information and previous knowledge of the measurand.

The pool of information may include

- previous measurement data;
- experience with or general knowledge of the behavior and properties of relevant materials and instruments;
- manufacturer's specification;
- data provided in calibration and other certificates;
- Uncertainties assigned to reference data taken from handbooks.

Uncertainty budget

It is the components of the measurement uncertainty and of their calculation and combination.

An uncertainty budget should include the measurement model, estimates, and measurement uncertainties associated with the quantities in the measurement model, co variances, type of applied probability density functions, degrees of freedom, type of evaluation of measurement uncertainty, and any coverage factor.

2.3 Task Specific Uncertainty

Task specific uncertainty is the measurement uncertainty associated with the measurement of a specific feature using a specific measurement plan. This is applicable to estimate task specific uncertainty for coordinate measuring systems [13]. A coordinate measuring machine (CMM) is a device to measure parts of different sizes and shape. This machine is both versatile and economical. The task of estimating uncertainty for CMM measurements is a difficult job as various kind of errors like part errors, machine errors, and environmental factors to contribute errors, surface sampling strategy, fitting algorithm etc affecting measurement result. The evaluation of uncertainty for CMM measurements for specific task is different than the general uncertainty statement that can be applied to all similar measurement [15]. For a specific measurement of CMM a large number of sampling strategy, different location of the part with the working volume, probe style and also various fitting criteria can be applied. Also In CMM-based measurements, a task-specific uncertainty for each and every geometric dimensioning and tolerancing (GD&T) parameter is necessary [14].

CHAPTER 3: TERMS AND DEFINITIONS

Everyday a large number of measurements are made in different sectors of life in the world. Terms and definitions are used in the measurement process in a common language for all the users over the world to facilitate the achievement of the goal of measurement process. There are many reasons to have such terms and definitions: to empower users to understand the measurement system and to make improvement of the quality of product; to assist in the transaction with other companies for local and global, consequently it will effect on economy positively. The products need to be made with greater accuracy in order to achieve quality and exist in the market. It is important to verify the measurement results and consequently verify the performance of the measuring equipments. Proper understanding and using common definitions and terms will help to check the reliability of the products and the measuring equipment. These are also important to make decision both for the suppliers and customers. Otherwise it will be very difficult to communicate or do business between each other. This chapter discussed terms and definitions in details. The definitions and figures are taken from industry, VIM (International vocabulary of metrology — Basic and general concepts and associated terms) and Measurement Systems Analysis (Reference Manual).

3.1 Definition of terms

Part

A part is an item that is subject to measurement.

Gage

A gage is any device that is used to obtain measurements.

Rated operating condition (Specification)

(From VIM)

> Operating condition is that which must be fulfilled during measurement in order that a measuring instrument or measuring system performs as designed.

Rated operating conditions generally specify intervals of values for a quantity being measured and for any influence quantity.

Maximum Permissible Error (MPE)

(From VIM)

> Limit of error extreme value of measurement error, with respect to a known reference quantity value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system.

Usually, the term “maximum permissible errors” or “limits of error” is used where there are two extreme values. The term “tolerance” should not be used to designate ‘maximum permissible error’.

Gage can be referring as artifact or measuring instrument. Gage block usually use as artifact and CMM, Micrometer usually use as measuring instrument. For the calibration of CMM, micrometer always mentioned specification and MPE (Maximum Permissible Error) are mentioned in the manufactured specification or in the reference manual. The specification and the MPE should not contradict each other or on the other hand these conditions should go together. CMM’s specification and MPE are mentioned.

CMM (Coordinate measuring machine)

Specification [General]

Normal temperature- 20^{0} C

Temperature variation - ± 3^{0} C

1. Test performed with Renishaw PH110M probe head, TP20 Probe and 20mm stylus

Maximum permissible error for size measurement MPE_{E}

Customer Specification 4.0+L/200 um

Maximum permissible probing error MPE_{p}

Customer Specification 6.2 um

2. Test performed with Tesastar probe and 20mm stylus

Maximum permissible error for size measurement MPE_{E}

Customer Specification 6.0+L/200 um

Maximum permissible probing error MPE_{p}

Customer Specification 8.2 um

Accuracy

(From VIM)

> Accuracy is the closeness of agreement between a measured quantity value and a true quantity value of a measurand.

The measurand is a quantity intended to be measured. The concept ‘measurement accuracy’ is not quantitative and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error.

Accuracy

(From Industry)

> Accuracy is the extent to which the average of the measurements differs from the true value.

It is the degree of closeness of a measured value to its actual (true) value.

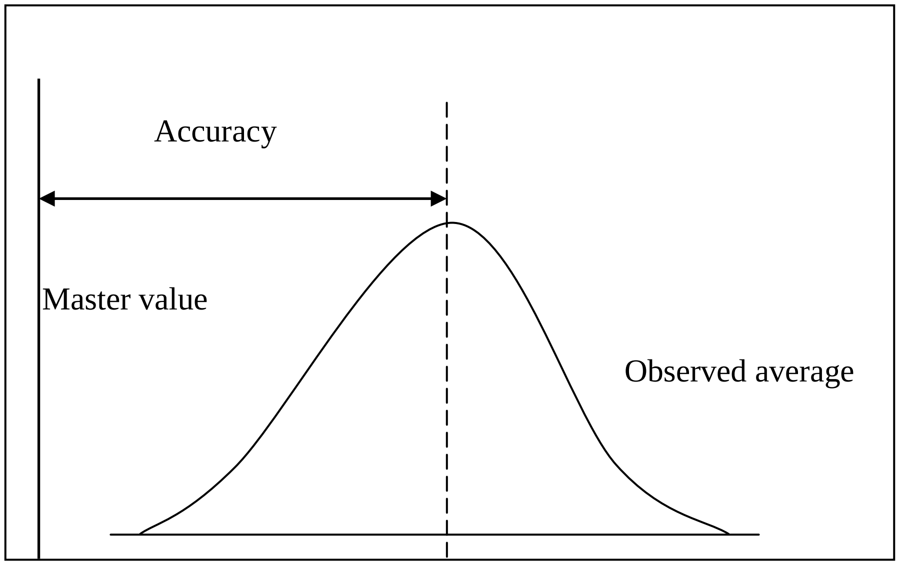


FIGURE 4: Accuracy

Bias

(From industry)
The bias, or offset, is how we quantify accuracy.

Bias is the difference between the average value of all the measurements (μ) and the true value (μ0). Bias is a measure of the amount by which a tool is consistently off target from the true value. Bias can be positive or negative.

Bias = μ-μ0

Because the exact true value is not possible to know, the 'best' estimate of the parameter being measured may be provided by the National Institute of Standards and Technology (NIST) or another national metrology institute (NMI). It can be used as a reference value, with a suitably low uncertainty.

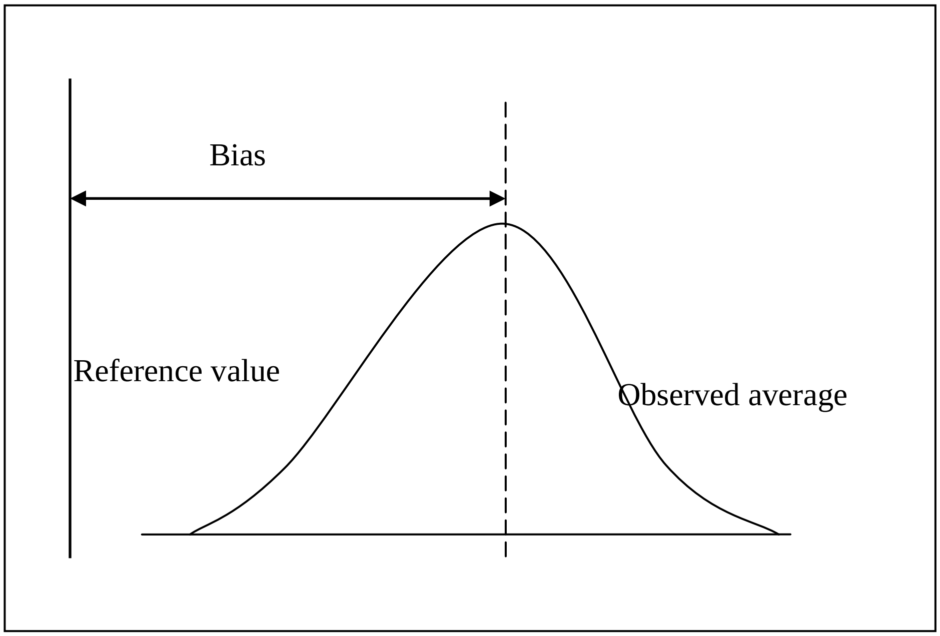


FIGURE 5: Bias

Precision

(From Industry)

Precision measures the natural variation of repeated measurements.

It is the total variation in the measurement system as quantified by σ_{ms} (Standard deviation of the measurement distribution). The smaller the standard deviation the better is the precision. It is the degree of closeness of the measured value with respect to each other.

Precision

(From VIM)

Precision is the closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions.

Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement. The ‘specified conditions’ can be, for example, repeatability conditions of measurement.

Repeatability

(From Industry)

It is the variation in measured value taken by a single person or instrument in the same part used by several times and under the same conditions.

The conditions are:

• Same operator

• Same set-up procedure

• Same environmental conditions

• During a very short period of time

Dynamic vs. Static Repeatability

Static repeatability

Static repeatability is the measure of the “inherent” variability in the measurement tool itself.

This is the variation from repeated measurements in which the part is not removed from the tool between measurements.

Dynamic repeatability

It is the measure of the “inherent” variability of the tool and measurement method.

It is the variation from repeated measurements in which the part is removed and re-fixture between measurements.

Repeatability

(VIM)

Repeatability is condition of measurement that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time.

Repeatability

(General)

It is the variation in measured value taken by a single person or instrument in the same part used by several times and under the same conditions.

It is also commonly known as equipment variation.

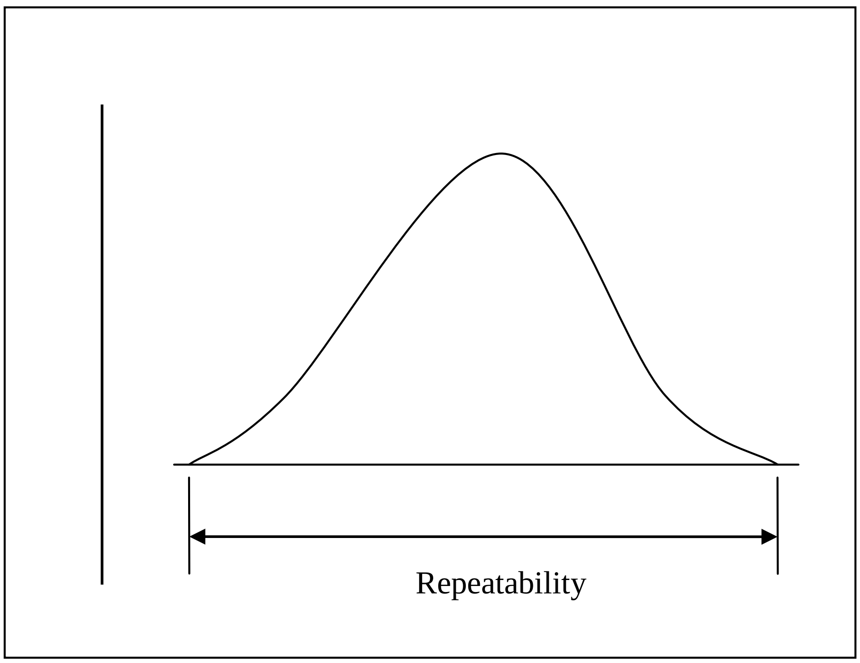


FIGURE 6: Repeatability

Reproducibility

(From Industry)

It is the variation in measured value taken by different persons with the same instrument in the same item used by several times and under the different conditions.

The conditions are:

- Different operators
- Different set-ups
- Different positions
- Different measurement media
- Different environmental conditions
- Over time

Reproducibility

(VIM)

Reproducibility is condition of measurement that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects.

The different measuring systems may use different measurement procedures.

Reproducibility

(General)

It is the variation in measured value taken by different persons with the same instrument in the same item used by several times and under the different conditions.

It is commonly known as appraiser variation.

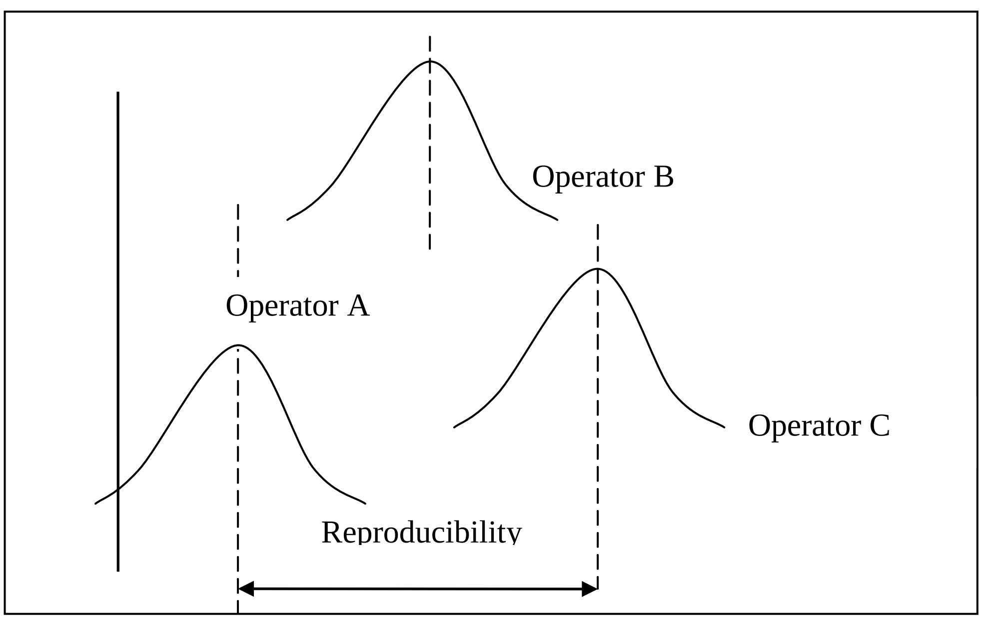


FIGURE 7: Reproducibility

Linearity

(From Industry)

Linearity is the consistency of the measurement system over a wide range of measurements.

Linearity

Linearity is the difference in the bias values through the expected operating range of the gage.

Stability

(From Industry)

A stable measurement system is one where the distribution of measurement errors remains constant and predictable over time, with respect to:

• Mean (Accuracy)

• Standard Deviation (Precision).

A stable measurement system has measurement error with:

• No drifts

• No sudden shifts

• No outliers

Stability is evaluated using a control chart -- a plot of the data in time sequence, with control limits.

Stability

(General)

Stability is the total variation in the measurements obtained with a measurement system on the same master or parts when measuring a single characteristic over an extended time period.

Stability is sometimes referred to as drift.

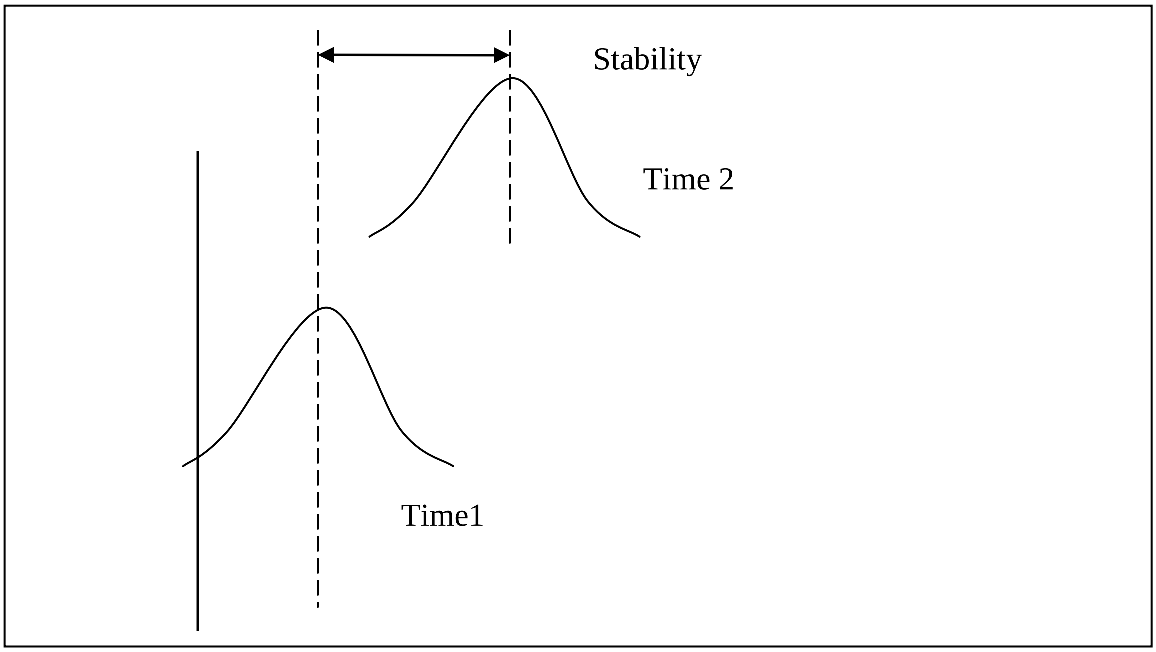


FIGURE 8: Stability

Part Variation

The Part Variation is a measure of the variation of the process.

If a large number of parts made by a process are measured, 99% (5.15 s) of the parts would be within the variation limits. The Part Variation is always less than or equal to the total variation. In most industrial processes the part variation is large compared to the gage variation and so the assumption that the observed standard deviation is approximately equal to the total population standard deviation holds good.

Capability

(From Industry)

The capability of a measurement system is the amount of the spec window that is lost to measurement error.

The capability of a manufacturing process is its ability to meet its specifications.

Metrology Tool Correlation and Matching

(From Industry)

Correlation

If two measurement systems are correlated, there is a reliable way to associate the measurements from the two sites.

Two systems can be correlated without being matched.

Matching

If two measurement systems are matched, their measurements are equivalent.

Matched systems are also correlated.

Task specific uncertainty

This is the uncertainty explicitly for a specific task. Usually it refers the measurement with the coordinate measuring machine for a definite measurement plan.

Sources of uncertainty for this are various as it has many different approaches of sampling strategy, fitting and evaluation algorithms, hardware etc. So the estimation of total uncertainty for a specific task with CMM is difficult. Some well known simulation methods to estimate uncertainty for a specific task is simulation by constrain (SBC), “Virtual CMM”.

No Relationship

If two measurement systems are not correlated and not matched, there is no reliable way to associate the measurements from the two measurement systems, so the metrology cannot be transferred. Corrective action for one or both of the measurement systems would be necessary to improve the equivalence of the two systems.

From all the definitions which are discussed above for Test Uncertainty Ratio, understanding of task specific uncertainty is very important and for Test Uncertainty it is important to know the specification and MPE for any instrument. If the instrument is specified in the temperature range 19 to 21 degrees, a temperature of 20.5 is not a part of test uncertainty. But a temperature of 21.5 degree means the temperature is no longer in specification. If it is considered that the temperature should be control by tester (Who is performing test) then the uncertainty due to this temperature should be part of test uncertainty. Manufacturing companies' achievement and collapse depend on the production of high-quality products. Proper understanding and implementation of the definitions and terms is the core for companies' success.

CHAPTER 4: CURRENT US AND ISO STANDARDS

The term “Standardization” can be defined as a method to support technical standards. A technical standard is usually a document that establishes consistent industrial methods or technological processes. The International Organization for Standardization is one of the primary organizations whose main activities are developing and maintaining standards for specifying the basic SI quantities such as length (the meter), time (the second), and mass (the kilogram). Standards also guide the evaluation of different measurement methods around the world. As it is important to maintain the interchangeability of components that are manufactured with different machines and inspected with different measurement processes, standards provide assurance of part quality through the calibration and traceability of measurement process. International standards play a crucially important role in all industries for rational production, international terminologies, safety and health protection, measurement, analysis, quality control and environmental protection [16].

The VIM defines that there are different terms and definitions in a hierarchical system and these can be classified as primary, secondary etc. Calibration is one of the process by which national standards of measurement are disseminated to end users in trade, industry, and scientific laboratories [2] and traceability is the ability to verify the history, location, or application of an item by means of documented recorded identification [17]. The term traceability is also used to refer to an unbroken chain of comparisons relating an instrument's measurements to a known standard and calibration to a traceable standard can be used to determine an instrument's bias, precision, and accuracy [18]. This chapter explains current international (ISO) and national (ASME) standards that apply to the application of decision rules between customers and suppliers, the estimation of uncertainty for different measurement situations, and the calculation of test uncertainty for different CMM performance tests.

4.1 ISO14253-1:1998(E)

(Geometrical Product Specifications (GPS)—Inspection by measurement of work piece and measuring equipment)

One function of industrial measurement is to determine whether a particular part measurand (length, form, location, etc.) conforms to the specification given on the part drawing or model. The difference between the specification zone and the conformance zone for a measurand is explained with the aid of FIGURE 9, taken from ISO 14253-1:1998(E).

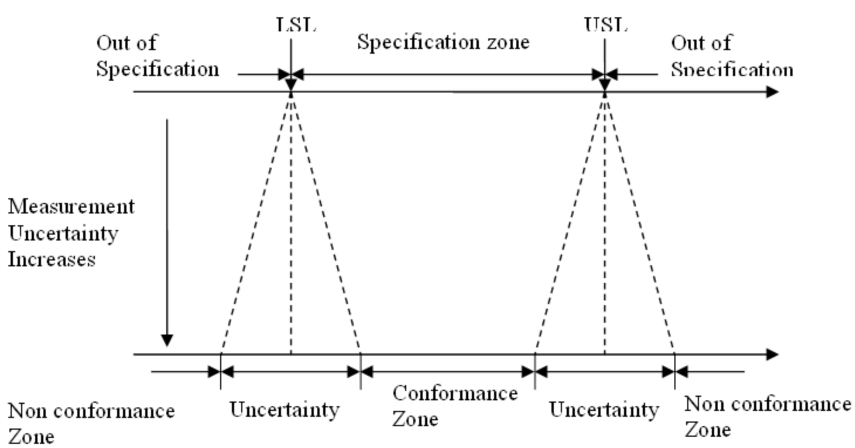


FIGURE 9: Relationships between Specification Zone and Conformance Zone

The upper horizontal line of the figure shows the specification zone, which is bounded by the lower specification limit (LSL) and the upper specification limit (USL). If the "true value" of the measurand is within the specification zone, then the specification is satisfied, otherwise the measurand is out of specification. However, we can never know the "true value" of the measurand. In order to state whether we believe that the measurand is in or out of specification, we have to acknowledge the existence of uncertainty in the measurement process. This is shown in the lower horizontal line in FIGURE 9. If the measurand is in conformance zone, we are suitably confident that the true value is in specification. Similarly, if the measurand is in the non-conformance zone, we are confident that the true value is out of specification. For the uncertainty region shown between conformance and non-conformance, we need to apply the "Decision rules." A decision rule is a method – agreed on by two parties – to decide whether to accept or reject a part when the measurement value lies in this uncertainty region. Estimation of uncertainty is very vital because if the uncertainty is too low which implies the size of conformance zone will be larger so there is possibility to accept some parts which are out of specification. At the same time if the uncertainty is too large which implies the size of the conformance zone is smaller so there is a possibility to reject some parts which are in specification. The contributors of the uncertainty which are mentioned in ISO/TR 14253-2 should be considered carefully to estimate the uncertainty more accurately and consequently it will help to apply decision rule more precisely.

4.2 ASME B89.7.3.1-2001

(Guidelines for decision rules: Considering measurement uncertainty in determining conformance to specifications)

One common decision rule used in industry is "Simple Acceptance and Rejection Using an N: 1 Decision Rule" as defined in ASME B89.7.3.1-2001. Using this decision rule, the measured value is compared directly to the specification zone (i.e. the conformance zone and the specification zone are identical). This rule has the effect of dividing the risk for accepting bad parts and rejecting good parts between the supplier and customer. In order to limit this risk, the requirement of N:1 is placed on the decision rule (N is often 4). In FIGURE 10 below, taken from the B89.7.3.1 document, the acceptance and rejection zones are shown to be identical to the specification zones.

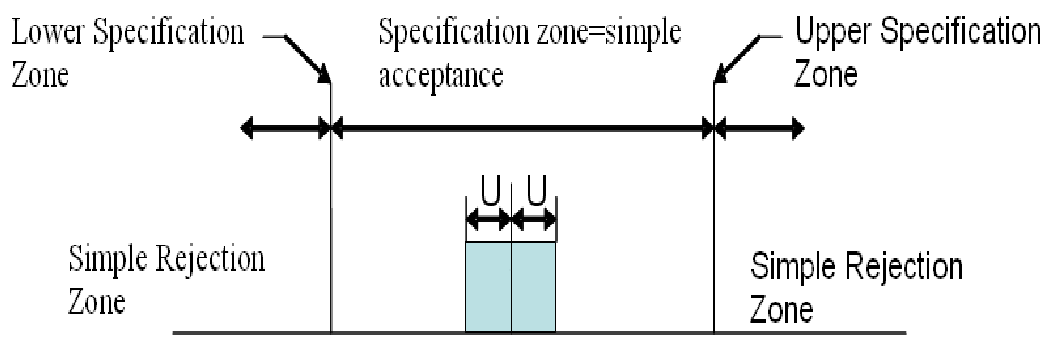


FIGURE 10: Schematic view of Simple acceptance/rejection

The measurement uncertainty interval is of width 2U, where U is expanded uncertainty, and the uncertainty interval is no larger than one-fourth the product's specification zone for N = 4. [B 89.7.3.1-2001] For the simple acceptance rule with a 4:1 ratio means that the tolerance range is at least 4 times the uncertainty interval. The part will be accepted if the measurand lies in the specification zone as long as it accomplishes the uncertainty constraint. Otherwise the part will be rejected. Another term maximum permissible error (MPE) is sometimes defined by the manufacturer for some instruments.

It is refer as ±MPE, so specification zone is twice the MPE value. In this case the decision rule is MPE is 4 time than the expanded uncertainty. If the measurand lies close the specification limits to avoid any part in out of specification an alternative decision rule based on “guard banding” is used. Guard band (defined in B 89.7.3.1-2001) is the magnitude of the offset from the specification limit to the acceptance or rejection zone. In this case new terms stringent acceptance zone and relaxed rejection zone are introduced which are shown in FIGURE 11 taken from this standard.

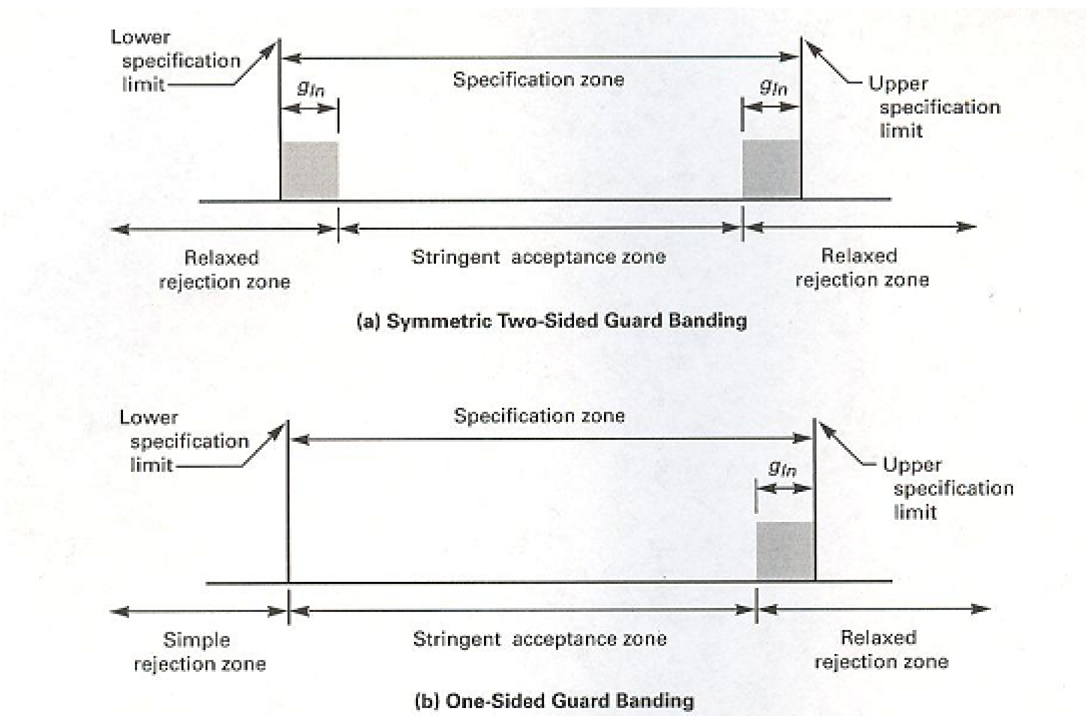


FIGURE 11: Stringent acceptance and relaxed rejection

For the special case when customer requested for stringent acceptance then the supplier go for this. In this case acceptance zone is reduced by the amount of guard band which is called stringent acceptance. On the other hand relaxed rejection zone reject the parts with the measurand lies in the specification zone by the amount of guard band.

4.3 B 89.7.4.1-2005

(Measurement uncertainty and conformance testing: Risk analysis)

This standard is the combination of some statistical definitions. One of them is Measurement capability index, Cm which is the ratio between tolerance to uncertainty. For two-sided tolerance zone of width T, $Cm=T/4u_m=T/2U$ where u_m is the standard uncertainty associated with the estimate of the characteristic. One sided tolerance zone of width T, $Cm=T/2u_m$ = $=T/2U$. In the case of calibration or verification of a measuring instrument with specified, maximum permissible error ±MPE, $Cm=T/2u_e$ = 2MPE/2U= MPE/ U; [Here T= 2MPE] where u_e is the standard uncertainty associated with the instrument error. One can know the quality of the measurement system from measurement capability index. It has some similarity with Test Uncertainty Ratio (TUR), Test accuracy ratio (TAR), gauge maker's rule.

4.4 ISO/TS 23165

> (Geometrical product specifications (GPS) -- Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty)

This standard describes the specific application of test uncertainty for coordinate measuring machine (CMM). This is the first standard for test uncertainty. Test Uncertainty is defined in this document as the expanded uncertainty U, associated solely with the testing instrument and its use in the test. This describes how to find the measurement quality of the test. Test uncertainty is the uncertainty for which the "tester" is responsible when evaluating an instrument. Contributors to the test uncertainty may include the uncertainty of the reference artifact used by the tester and details of the tester's measurement procedure that result in errors and uncertainty. For example when CMM is calibrating by using an artifact, the error contribution from CMM should not be included in test uncertainty budget. So the instrument error is not the part of test uncertainty. The error contribution from the artifact and the tester (who is doing the test) should be included in test uncertainty budget. So the uncertainty contributors of test uncertainty is small than the contributors of measurement uncertainty. So this standard modifies the conformance and non-conformance zones, according to the decision rule in ISO 14253-1.

4.5 ASME B89.4.1

(1997 Methods for performance evaluation of coordinate measuring machines)

To verify the CMM performance being accepted or re-verified when it is tested based on the ISO 14253-1 to prove conformance or non-conformance, ISO 10360-2 helps to take decision rule. It explains the performance of the CMM used for measuring size is verified if the error of indication of a CMM for size measurements, E, is not greater than the maximum permissible error of indication of a CMM for size measurements, MPE_E, as specified by the manufacturer and taking into account the uncertainty of measurement according to ISO 14253-1. This standard also defines the measurement capability index $Cm \geq 4$ which describes that expanded test uncertainty is not greater than one fourth of the maximum permissible error (MPE). In any case if $Cm < 4$, it should be declare in data sheet. To test the CMM by using the artifact in this case it must need to fulfill the requirement of Cm. CMM conformance test results are acceptable if they are inside the MPE value and also satisfies 4:1 rule.

4.6 ISO/TS 15530-3

(Geometrical product Specifications (GPS) - Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement - Part3: use of calibrated work pieces or standards)

This standard explains the experimental technique how to calculate the uncertainty for the measured feature by using CMM for different physical quantity like size, distance, position, form, location, datum, orientation. For each task one measurement plan is important – how one will handle the work piece and how many times need to do measurement and where to place the work piece. Any place within the range the work piece can be keep with good fixturing; at least 10 measurement cycles should be carried out. The uncertainty contributors should be handling carefully like temperature, cleaning, fixturing, other environmental factors etc. CMM need to be calibrated first and then start measurement. From measurement data one need to find standard deviation. Another important part of the calculation is bias estimation. We know bias is the difference between the average of the measurement data and the reference value. The reference value should be close to true value which can be taken from NIST that will give more accurate result otherwise it needed to be taken in a very good environmental condition. The equation for uncertainty measurement is.

$$U=|b|+ 2\sigma$$

This equation is the combination of both the standard deviation of the measurement process and also the bias which is the difference between the average measurement value and reference value. So this expanded uncertainty result is very useful as it indicates both the standard deviation of repeat measurements and the accuracy of the measurement results. Precision and accuracy both are essential for the reliability of measurement results. The measurement results how precise and accurate both are checked by this equation as a result quality of the products are estimated properly.

CHAPTER 5: TEST UNCERTAINTY RATIO (TUR)

Manufacturing companies' success depends on the production of good quality products. Precise measurement systems are essential to verify the quality of the product. Every measurement process contains variations, just as each manufacturing process does. Manufacturing variations need to be checked by the measurement tools. Measurement tools need to be verified also to insure the best quality of the products. If the variations of the measurement system are high enough, it may affect the whole manufacturing company, as the cost of poor product quality affects the entire manufacturing enterprise. It is essential for a manufacturing company to have a powerful method to analyze measurement systems. One such measurement analysis tool is the Test Uncertainty Ratio (TUR). Other analysis tools which are currently used in industries are Precision over Tolerance (P/T) and Gage Repeatability and Reproducibility (gage R&R).

5.1 Test Uncertainty Ratio (TUR)

The Test Uncertainty Ratio (TUR) is a measure of the ability of a particular measurement instrument and/or process to evaluate conformance to specification. TUR is the ratio between the tolerance or specification and the uncertainty present in the test of this tolerance or specification. Historically, the rule of thumb for an appropriate ratio was that the TUR must be at least 10:1.The higher the ratio, the better the performance of the test. In other words, the instrument can evaluate good vs. bad (conforming vs. non-conforming) parts with a high degree of confidence. Currently, a ratio of 4:1 or even 3:1

is considered acceptable. This is due mostly to the better performance of manufacturing equipment, and the tighter and tighter specifications on manufactured components. In many cases, test equipment with an uncertainty small enough for a 10:1 TUR does not exist, or is prohibitively expensive for the application.

There are two main applications of the TUR: the first is in the measurement capability of measuring instruments, the second is in the inspection of manufactured components. Only one metrology tool is available for this experiment, so it was not possible to compare the measurement capability of metrology tools. One example is used to explain how to use TUR to find the measurement capability of different tools. The second application is the main focus – how do we determine the Test Uncertainty Ratio for a part that we need to measure using a particular gage? The list below gives some of the important things to consider. Each of these topics will be covered in more depth in this chapter.

1. The uncertainty statement in the gage's product literature might not be the uncertainty needed to calculate TUR.
2. The result of the gage's most recent calibration is almost certainly not the uncertainty needed to calculate TUR.
3. The tolerance value on the part drawing is – if interpreted correctly – going to be needed to calculate TUR.
4. There will be more than one TUR calculation for a part if there is more than one tolerance that must be inspected.

For TUR the task-specific measurement uncertainty must be estimated for the measurand in question for each tolerance. This is the "1" value in the denominator. The range of allowable values for the measurand in question (this is usually the tolerance) must be known, and is the numerator of the ratio, which is compared to the "4" value. To determine the TUR, the ratio shown below is evaluated.

$$\text{TUR} = \frac{\text{Tolerance}}{\text{Task specific uncertainty}}$$

As is easily inferred from the equation above, the TUR ratio compares the allowable variation for the measurand (the numerator) with the variability associated with finding the measurand (the denominator).Test Uncertainty Ratio (TUR) will provide the information about the accuracy and precision of the system, which include repeatability, reproducibility. One method of evaluating the expanded measurement uncertainty for a task is to combine the short-term variability of the system with a bias of the system, as shown below. $U = |bias| + 2\sigma_{meas}$

The above equation for expanded uncertainty is taken from ISO 15530 which is described in Chapter 4. This equation is very useful for checking both the precision and accuracy at a time.

In calculating TUR, the tolerance is in the numerator, but the question is how to find the appropriate value for the denominator which may be task specific uncertainty, the maximum permissible error value of the CMM or the actual result of the CMM calibration. So, to apply the 4:1 rule one could consider:

1) The CMM specification vs. tolerance
2) The CMM calibration value vs. tolerance
3) The task specific uncertainty vs. tolerance

Let’s take part tolerance 25µm.

1) In the case of CMM specifications (the MPE value) which are mentioned,

usually in the manufacturer's specification.

Let's consider $MPE_E = 6\mu m$. In this case, TUR= 25µm / 6 µm ≈ 4:1

2) In the case CMM calibration value, let's consider the CMM was calibrated recently and the E value turned out to be 5µm.

In this case, TUR=25µm / 5 µm ≈ 5:1

Both of these experiments were done with the artifact. Neither of these calculations takes into account the sampling strategy of the part like number of measurements, number of points, alignment, fixturing, clamping. From the above discussion, it is found that the TUR can be used to find the end product's quality. To calculate TUR one should emphasize how the part is measured. We therefore recommend that the third method be used.

3) The task specific uncertainty should be calculated for each tolerance, and this value used when calculating the TUR.

Let's consider when measuring a part, task specific uncertainty for the first measuring tool is 4 µm and for the second measuring tool is 5 µm.

In the first case, TUR= 25µm / 4 µm≈ 6:1 and in the second case, TUR= 25µm / 5 µm ≈ 5:1

The first measurement tool's measurement capability is better than the second as the value of TUR in the first case is larger than in the second.

One can easily estimate the measurement uncertainty for a simple measurement like the length of a block using instruments like the micrometer or slide caliper. In this case the results will give a direct reflection of the instrument error, so the measurement process for this is very simple. FIGURE 12 and FIGURE 13 show the measuring task and the micrometer. But for more complicated measurements like the true position of a hole, shown in FIGURE 14, the results will not give a direct reflection of the instrument error. For these types of measurements, complex metrology systems such as Coordinate Measuring Machines (CMMs) (FIGURE 15) are required.

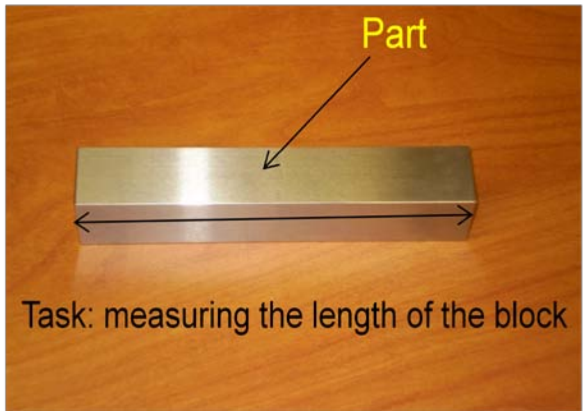


FIGURE 12: Measuring a part

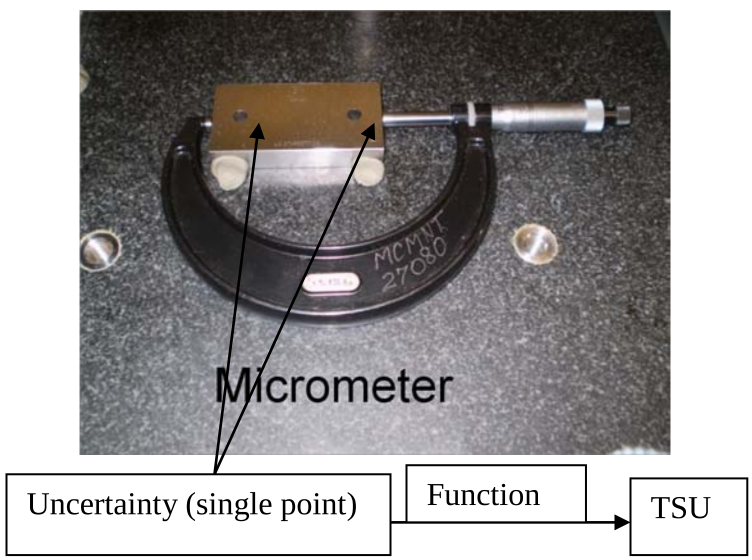


FIGURE 13: Micrometer

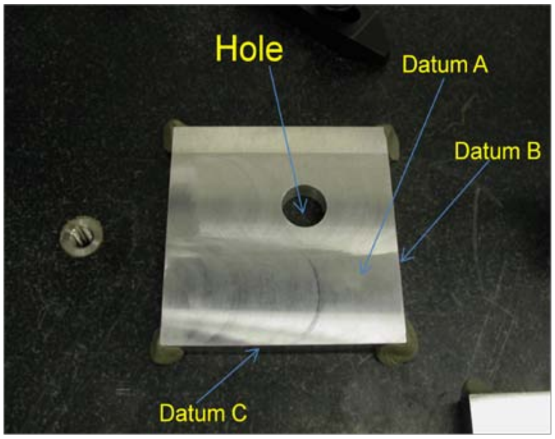


FIGURE 14: Measure the position of the hole

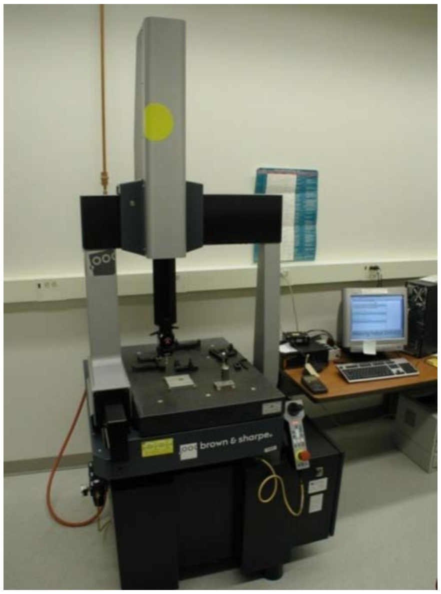


FIGURE 15: CMM

There are many simulation methods that help to estimate the task specific uncertainty in coordinate measurement. Various names are given to these simulation methods like Virtual CMM, Simulation by constraints, Monte Carlo simulation [13].

5.2 TUR Contributors

It is important to know the contributors that affect the TUR, which will help to calculate TUR. FIGURE 16 shows the contributors to the task specific uncertainty, which is necessary to find the TUR.

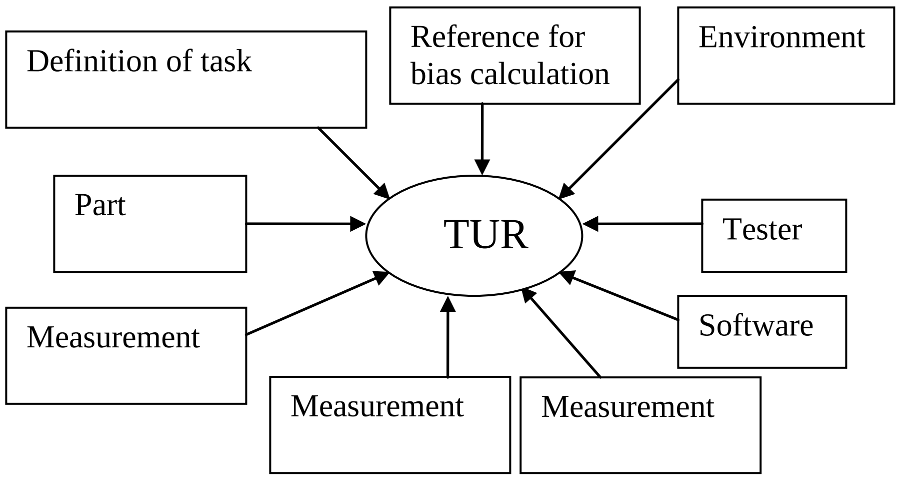


FIGURE 16: Contributors to TUR

The different contributors to the TUR shown in FIGURE 16 are described below.

Definition of task

The task needs to be determined first. It may be size, true position, or any other characteristic of interest. For every task one needs to calculate TUR individually and tolerance needs to be determined separately. For example if one needs to calculate TUR for both size and true position, then the tolerance values for each should be known separately and used in the appropriate TUR calculation.

Part Tolerance

The tolerance for every task needs to known to calculate TUR. In the case where one is trying to determine the limiting tolerance value that can be inspected, this can be obtained by using the lowest acceptable value of TUR and the task-specific uncertainty for that measurand.

Reference value

The reference value may be needed to calculate the bias for a particular measurement. The uncertainty of this value will be lowest if it is obtained from an NMI, but a reference value with a suitably low uncertainty from another reliable source is acceptable.

Environment

Temperature, vibration, dust, etc may influence the value of Uncertainty. So these factors need to be taken into consideration when measuring the part.

Measurement Tool

The ability of the measurement tool to measure the part accurately has the greatest influence on the value of TUR. The long term stability and short term stability of the measurement tool should be checked to track the performance of the measurement equipment. However, it is a mistake to think that this is the only source of uncertainty.

Measurement set up

If the set up of both the part and the tool is not perfect, the measurement result can vary. The position of the part needs to be perfect and clean enough to get the expected result. Measurement set up should be checked properly so that everything stays stable when the measurement process continues.

Measurement procedure

One needs to use the measurement procedure as defined for each measurement tool. If the measurement procedure like number of measurements, duration of measurements, strategy, number of points, order of measurement are not followed properly the measurement result may not outcome as expected.

Software

The measurement results depend on the software which is used for acquiring measurements and analyzing measurement data. The quality of the analysis tools also plays an important role in getting expected results. Even for the same measuring instrument different analysis tools may give varying results.

Tester

Test results depend on how expert the tester is. Testers' experience, education, training, knowledge, performance influences measurement results significantly.

All the contributors described above except tolerance have influence on task specific uncertainty and consequently TUR.

"PUNDIT" is commercial software for CMMs that simulates task specific uncertainty. This software was used for this project to estimate task specific uncertainty by simulation. This allows data input like part tolerance, CMM specifications, environmental conditions, sampling strategy, manufacturing information that accordingly gives a very good reflection of actual experiment results. MATLAB program is also used in this project to estimate task specific uncertainty. MATLAB program is widely used both for academic purpose and in industry. This method can use data files for the sampling strategy of the part but it did not include input for environmental conditions. As environment is a main contributor of uncertainty, these results could not be as close to the experimental results. PUNDIT and MATLAB were used to get theoretical results. PC-

DMIS is a CMM software to estimate task specific uncertainty for the practical experiments.

5. 3 Other Metrics

5.3.1 P/T ((Precision-to- Tolerance) Ratio

P/T ratio and gage R &R are other metric used in the industries to find the measurement capability of the metrology tool.

Below P/T and Gage R&R are described.

The P/T Ratio

(From Industry)

The capability of the measurement system is quantified by computing the P/T (Precision-to- Tolerance) Ratio.

For two-sided specs (both USL and LSL):

$$P / T = \frac{6\sigma}{Tol} \text{ x}100\%$$

For one-sided specs (either USL or LSL, or if no spec limits exist):

$$P / T = \frac{3\sigma}{Tol} \text{ x } 100\%$$

Where: TOL = (Process Mean or Target - LSL) for LSL only,
= (USL - Process Mean or Target) for USL only,
= 3*(Expected spread in data, S process) if spec limits do not exist.

Note: If a process mean can be estimated, then it is not recommended to define TOL as (Target - LSL) or (USL - Target) because using a Target value underestimates the true P/T ratio.

- P/T expresses the percentage of the spec window that is lost to measurement error.
- Small values of P/T are desirable.
- P/T ≤ 30%: Measurement system capable.
- P/T > 30%: Measurement system not capable (not precise enough).

5.3.2 Gage Repeatability and Reproducibility (Gage R & R)

There are three basic and widely used methods for determining the Gage R&R. They are:

- Range method
- Average and Range method
- Analysis of Variance method (ANOVA)

The Average and Range method is discussed in detail.

The Average and Range method is a statistical method that provides an estimate of the following components-Part Variation, Repeatability, Reproducibility, R&R, Total Variation.

This method computes the total measurement system variability, which can be separated into components like repeatability, reproducibility and part variation. This method involves multiple parts, appraisers and trials to quantify the total variations of the system.

Consider a measurement system which involves 10 parts, 3 operators and 3 trials. For each operator, it is necessary to compute the average of the part and trial readings. As an example consider,

For operator A total average of the measurements is $\bar{X}_a$

For operator B total average of the measurements is $\bar{X}_b$

For operator C total average of the measurements is $\bar{X}_c$

The average range of the measurement made by operators A, B and C are $\bar{R}_a$, $\bar{R}_b$ and $\bar{R}_c$

The average of $\bar{X}_a$, $\bar{X}_b$ and $\bar{X}_c$ is $\bar{\bar{X}}$. The average of $\bar{R}_a$, $\bar{R}_b$ and $\bar{R}_c$ is $\bar{\bar{R}}$ $\bar{\bar{R}}$.

With the above definitions,

Upper control limit (UCL) for range chart = $D_4 \times \overline{\overline{R}}$

Lower control limit (LCL) for range chart = $D_3 \times \overline{\overline{R}}$

Where D_4 and D_3 are control chart constants and can be obtained Appendix C in [1].

With the above data we can calculate following terms.

Repeatability

Repeatability is commonly referred to as Equipment Variation (EV)

$$EV = \overline{\overline{R}} * K_1$$

Where K_1 is constant.

$K_1 = 5.15/d_2$ where d_2 depends on the number of trials (m) and the number of parts times the number of appraisers (g). The value of d_2 is obtained from Appendix D. All calculations are based upon predicting 5.15s (99% area under the normal curve).

Reproducibility

Reproducibility is commonly referred to as Appraiser Variation (AV)

$$AV = \sqrt{(\overline{X}_{DIFF} * K_2)^2 - (EV^2 / nr)}$$

$K_2 = 5.15/d_2$ where d_2 depends on the number of appraisers (m) and g is 1, since there is only one range calculation. n = number of parts and r = number of Trials

If a negative value is calculated under the square root sign, the value AV defaults to zero.

Repeatability and Reproducibility (R&R)

The variation for repeatability and reproducibility is obtained by taking the root of the sum of the squares of the appraiser variation and equipment variation.

$$R \& R = \sqrt{EV^2 + AV^2}$$

Part Variation (PV)

The part variation is determined by multiplying the range of part averages by a constant. $PV = R_p * K_3$

Here R_p is the range of the part average $\overline{X}_p$.

$K_3 = 5.15/d_2$ where d_2 is dependent on the number of parts and number of appraisers.

Total Variation (TV)

The total variation is the square root of the sum of the squares of the variation for repeatability and reproducibility (R&R) and the part variation.

$$TV = \sqrt{(R\&R)^2 + (PV)^2}$$

Percent of Total Variation

The variability of each factor determined above can be compared with the Total Variation (TV). The percent of equipment variation of the total variation is computed as

%EV = 100(EV/TV)

The percent of other factors can be calculated as follows.

%AV = 100(AV/TV)

%R&R = 100(R&R/TV)

%PV = 100(PV/TV)

The sum of percentages of the each of the above factors will not equal 100%. The results could also be given as a percentage of the tolerance specification depending on the requirements. In that case, the total variation in the denominator is replaced by the tolerance specification.

The metrics P/T and gage R&R both are reflecting how precise measurement results are. These do not give any impression of accuracy of measurement results or how close the measurement results to the reference value. Accuracy is also very important for part measurement. To get the best result, measurement results need to be both precise and accurate. For the metric P/T, in industry, accuracy is calculated separately. But for gage R&R it may give a wrong impression of the measurement result as accuracy is not checked. TUR is giving the reflection of both precision and accuracy. So this is a very power method comparing to other two methods.

5.4 Calculation of TUR

The block shown in FIGURE 17 is the model for simulation by the PUNDIT software, MATLAB, and practical experiment by using PC-DMIS software for CMM. The dimensions and tolerances for the part are shown in FIGURE 18. Task specific uncertainty was estimated by all these methods. They are described below accordingly. Two tolerances are evaluated: a size tolerance (the width of the block) and a position tolerance for the circular feature. In both cases the tolerance value on the drawing is 0.025mm. It will be shown that for the different features, and different measurement strategies, the TUR value will be different.

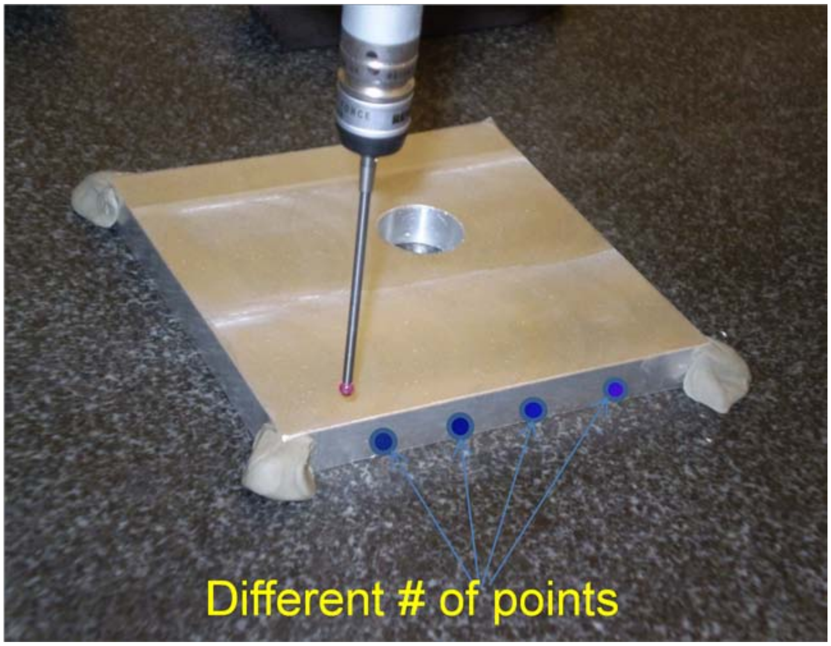


FIGURE 17: Block (100mm x 100mmx 10mm)

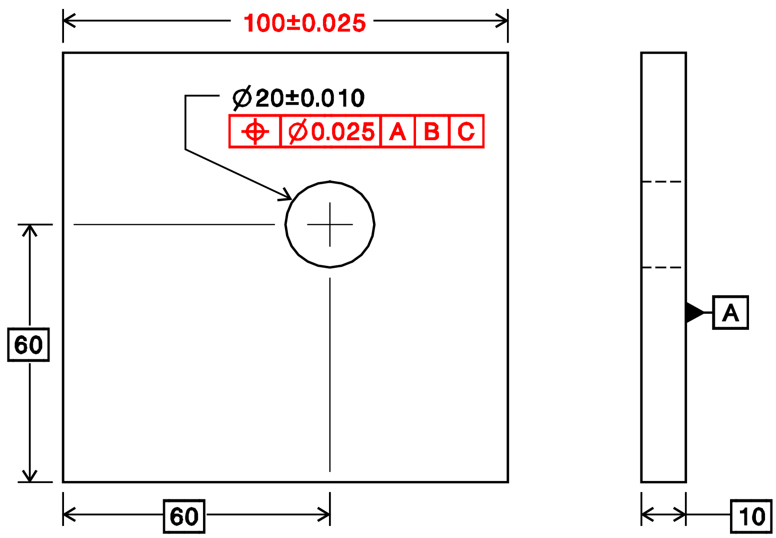


FIGURE 18: A simple part with size and position specifications

5.4.1 Simulation method (PUNDIT)

To evaluate this, several simulations have been done using the PUNDIT software. For this simulation the E-value of the CMM will be estimated at 6μm and the results of the simulation will be the task-specific uncertainty for each tolerance.

For the size tolerance, different numbers of points were taken 4, 12 and 30 along the opposite ends of the block. In FIGURE 19-a, 12 points are shown along the one end of the block. Twelve points were also taken on the opposite plane. FIGURE 19-b shows the result (the task specific uncertainty) from the simulation. TABLE 1 summarizes the expanded uncertainty and TUR for different numbers of points used in the size measurement.

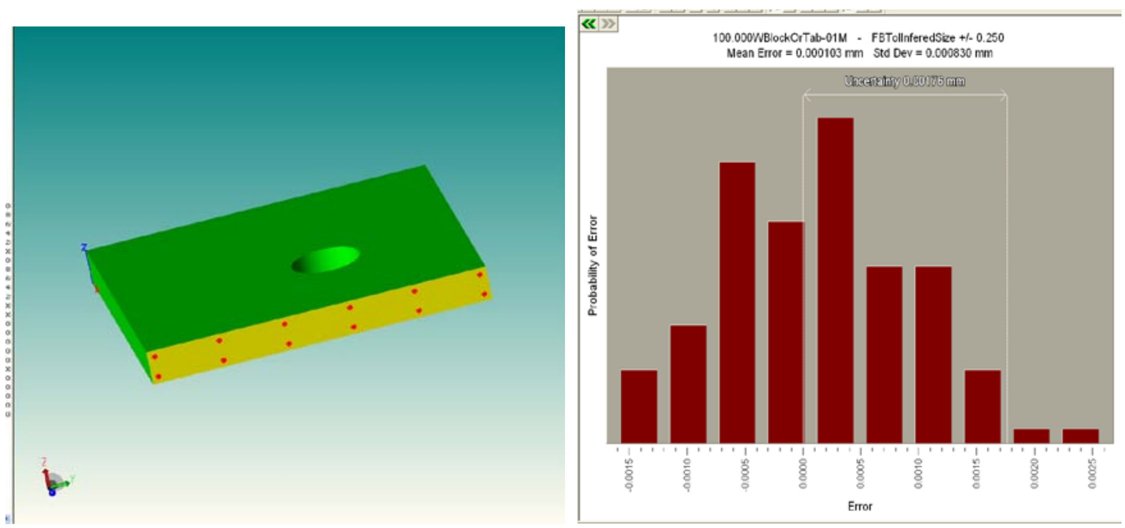


FIGURE 19: Test part/Simulation result

a) Test part with measurement points shown b) results of simulation for size tolerance

TABLE 1: TUR values for size tolerance by using PUNDIT simulation

Block Length		
# points	U (μm)	TUR
4	1.61	30:1
12	1.46	35:1
30	1.35	40:1

The position tolerance will be discussed now. Different numbers of points were taken on a circular feature (6, 16 and 30 points) and different numbers of points were taken also on each of the Datum features: A, B, and C as shown in FIGURE 20 below. In each case 4 points were taken on Datum A (the top); either 2 or 4 points were taken on Datum B and C on the sides. "4, 2, 2" refers to 4 points on Datum A, and 2 each on Datum B and C. "4, 4, 4" refers to 4 points on Datum A, and 4 each on Datum B and C. FIGURE 21 shows the simulation results for position tolerance from PUNDIT. TABLE 2 summarizes the expanded uncertainty and TUR for different numbers of points used in the position measurement.

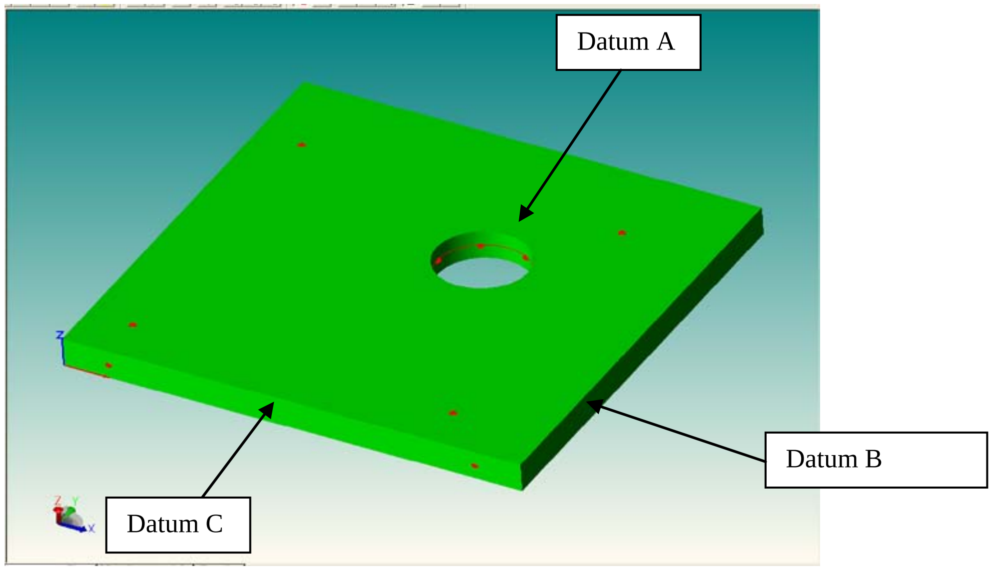


FIGURE 20: Datum A – 4 points, Datum, Datum C – 2 Points,

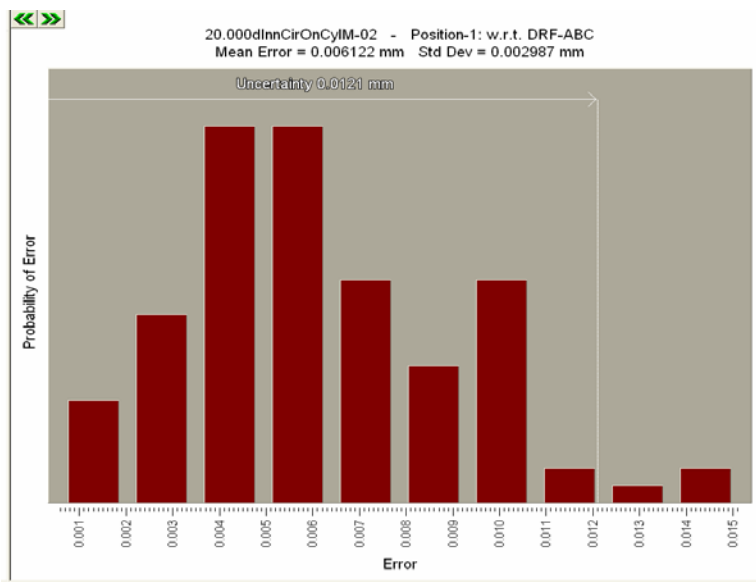


FIGURE 21: PUNDIT results of simulation for the position tolerance for the hole

TABLE 2: TUR values for the Position Tolerance by using PUNDIT simulation

Circle # of points	Uncertainty and TUR with datum points 4, 2, 2		Uncertainty and TUR with datum points 4, 4, 4	
	U (μm)	TUR	U(μm)	TUR
6	6.94	4:1	4.19	6:1
16	6.61	4:1	4.01	6:1
30	6.03	4:1	3.74	6:1

Both TABLE 1 and TABLE 2 show that for the same tolerance the TUR values are different for size, position, and in some case also depending on the number of points measured. In both cases, by increasing the number of points, task specific uncertainty decreased. In the size case, by increasing the number of points, TUR value increases, which is expected. In the position case, there is more dependence on the datum measurement than the circle sampling strategy.

5.4.2 MATLAB Program

MATLAB programs were used to find task specific uncertainty and consequently the TUR. These programs used “Monte-Carlo” simulation of random errors. In the case of size, it was possible to generate lines, different numbers of points, and find the distance between two lines. For the case of position, it was possible to generate datums, datum points, circle points, and estimate true positions of the hole. The number of points in MATLAB was taken in one row, but in PUNDIT and practical experiment they were taken in two rows, however the number of points was the same. In the MATLAB program uncertainty-contributors like temperature were not included so the task specific uncertainty results were very small in comparison to PUNDIT and the actual experiments. The MATLAB programs are in Appendix A. TABLE 3 and TABLE 4 summarized the expanded uncertainty and TUR for different numbers of points used in the size and position measurement.

TABLE 3: TUR values for size tolerance by using MATLAB program

Uncertainty and TUR		
# points	U (m)	TUR
4	0.67	75:1
12	0.41	121:1
30	0.27	185:1

TABLE 4: TUR values for position tolerance by using MATLAB program

Circle # of points	Uncertainty and TUR with datum points 4, 2, 2		Uncertainty and TUR with datum points 4, 4, 4	
	U (μm)	TUR	U(μm)	TUR
6	0.71	35:1	0.70	34:1
16	0.41	61:1	0.39	58:1
30	0.33	75:1	0.31	69:1

In TABLE 2 and TABLE 3, it is shown, increasing the number of points both on the circle and on the datums uncertainty values decreased and consequently TUR values increased (Task specific uncertainty is in the denominator of the TUR equation). So the results are giving a good reflection of what was predicted.

5.4.3 Experiment

Actual experiments were completed for the same block by using PC-DMIS software for the CMM. The numbers of points taken were the same in actual tests as for simulation, both for size and position. FIGURE 22 shows the CMM with the actual part.

TABLE 5 and TABLE 6 summarize the expanded uncertainty and TUR for different numbers of points used in the size and position measurement.

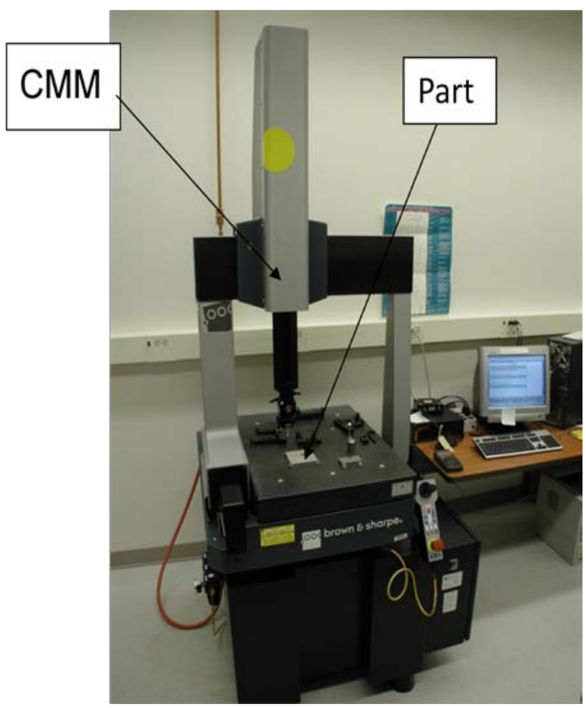


FIGURE 22: CMM with part

TABLE 5: Experimental results of size tolerance by using PC-DMIS software

Uncertainty and TUR			
# of points	2σ (μm)	U(μm)	TUR
4	0.97	16.45	4:1
12	0.84	15.04	4:1
30	0.63	14.38	4:1

TABLE 6: Experimental results of position tolerance by using PC-DMIS software

# of points	Uncertainty and TUR with datum points 4,2,2			Uncertainty and TUR with datum points 4,4,4		
	2σ (μm)	U(μm)	TUR	2σ (μm)	U(μm)	TUR
6	1.29	10.29	2:1	1.78	9.57	3:1
16	1.62	9.38	3:1	1.36	8.03	3:1
30	1.56	9.01	3:1	1.21	7.98	4:1

TABLE 5 and TABLE 6 show that by increasing the numbers of points, standard deviation and uncertainty values decreased as predicted. TUR value did not change since bias dominated the results.

5.5 Comparison results between PC-DMIS, PUNDIT and MATLAB

For TUR calculations, tolerance of the part and the task specific uncertainty are required. Tolerance of the part was the same for all cases; only the other contributor, task specific uncertainty influences the TUR value. As task specific uncertainty is in the denominator the smaller the value of this the better the result of TUR. In TABLE 7and TABLE 8 task specific uncertainty were compared for these three methods both for size and position. From these tables it is found that PC-DMIS results for task specific uncertainty are larger than the other two methods because in the practical experiment (using PC-DMIS software) all the contributors of uncertainty were present. Similarly, PUNDIT results are larger than MATLAB results because PUNDIT allows user to enter some uncertainty contributors. In the case of MATLAB only sampling strategy were changed, no uncertainty contributors were included.

TABLE 7: Comparison of size between PC-DMIS, PUNDIT, and MATLAB

Uncertainty			
# of points	PC-DMIS U (μm)	PUNDIT U(μm)	MATLAB U(μm)
4	16.45	1.61	0.67
12	15.04	1.46	0.41
30	14.38	1.35	0.27

TABLE 8: Comparison of position between PC-DMIS, PUNDIT, and MATLAB

# of points	Uncertainty and TUR with datum points 4,2,2			Uncertainty and TUR with datum points 4,4,4		
	PC-DMIS U (μm)	PUNDIT U(μm)	MATLAB U(μm)	PC-DMIS U (μm)	PUNDIT U(μm)	MATLAB U(μm)
6	10.29	6.94	0.71	9.57	4.19	0.70
16	9.38	6.61	0.41	8.03	4.01	0.39
30	9.01	6.03	0.33	7.98	3.74	0.31

5.6 Experiments for Steel and Aluminum plates

Experiments have been done to compare the TUR and P/T ratio for different measurement tasks. It is found P/T is the metric which is already being used in the industry. So TUR is compared with P/T though both are not the indication of the same parameters. P/T is only indicating precision, so bias is added separately in the tables to get an idea of the accuracy of the measurement results. It is expected that where P/T smaller the TUR value will be larger. This is reflected in some of the results but in some results it is not reflected properly as bias was dominating. As the task specific uncertainty for TUR was calculated by using the equation $U = |bias| + 2\sigma meas$, bias influenced the TUR values.

Two blocks, one made of steel and the other of aluminum, were used for these calculations are shown in Figure 24 and FIGURE 24. In case of size, 4, 12, 30 number of points were taken from left to right to find the distance between the 2 sides. In the case of position, 6,16,30 points were taken on the circles and 4,2,2 and 4,4,4 points were taken on the datums as were taken for earlier experiments and simulations.

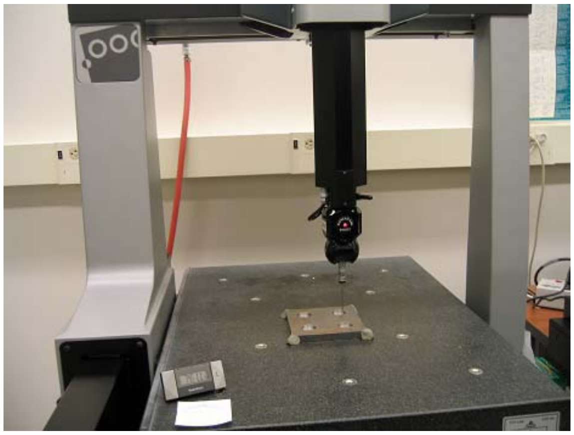


FIGURE 23: Steel block on CMM

FIGURE 24: Aluminum block on CMM

5.6.1 Size Tolerance results

The experimental results for the size tolerance of steel block are shown in TABLE 9 and TABLE 10

TABLE 9: Size Tolerance of Steel Plate

U, TUR, P/T, Bias for Steel plate by using PC-DMIS software					
#of points	2σ (μm)	U (μm)	TUR	P/T (%)	Bias (μm)
4	1.03	26.98	2:1	6.18	26.88
12	1.03	7.05	7:1	6.18	6.02
30	0.632	2.27	30:1	3.79	1.64

TABLE 10: Size Tolerance of Aluminum Plate

U, TUR, P/T, Bias for Aluminum plate by using PC-DMIS software					
#of points	2σ (μm)	U (μm)	TUR	P/T	Bias
4	0.843	41.80	1:1	5.05	41.37
12	0.632	9.65	5:1	3.79	9.02
30	0.500	9.44	5:1	3.0	8.94

In each case we can see that the bias introduced by uncorrected thermal changes, and the errors introduced by the point placement in the 4 point case result in a bias that dominates the short term variability of the measurements. Of course, an uncorrected bias is not something that we would expect to happen in ordinary measurements. However, if we do not know the extent to which certain errors occur (thermal drift, loose fixturing, etc.), this uncorrected bias may be introduced. The message that is hidden in these data is that a procedure that does not capture the bias, but only quantifies the repeatability, is at risk of over-estimating the capability of the measurement system. One such method that does not capture bias in repeated measurements is a GR&R study.

5.6.2 Position Tolerance Results

The experimental results for the position tolerance of the steel block are shown in TABLE 11and for the aluminum block are shown in TABLE 12.

TABLE 11: Position Tolerance of Steel Plate

# of points	Uncertainty and TUR with datum points 4,2,2			Uncertainty and TUR with datum points 4,4,4		
	2σ (μm)	U(μm)	TUR	2σ (μm)	U(μm)	TUR
6	2.74	27.94	1:1	1.49	26.63	1:1
16	1.92	27.68	1:1	1.18	26.17	1:1
30	1.56	27.77	1:1	1.09	25.90	1:1

TABLE 12: Position Tolerance of Aluminum Plate

# of points	Uncertainty and TUR with datum points 4,2,2			Uncertainty and TUR with datum points 4,4,4		
	2σ (μm)	U(μm)	TUR	2σ (μm)	U(μm)	TUR
6	2.69	70.48	0.354:1	1.63	67.57	0.369:1
16	1.24	68.48	0.365:1	1.25	66.72	0.374:1
30	0.526	67.20	0.372:1	0.34	64.79	0.385:1

It is found in the tables above that the 2σ spread of data from multiple measurements is improved by taking more points on the datum features, but because the bias in the results is so large, by comparison, this improvement is not reflected in the TUR values. TABLE 13 shows the P/T ratio for these measurements for steel block and TABLE 14 for aluminum block along with the bias in both X and Y.

TABLE 13: P/T and Bias of steel plate

# of points	Uncertainty and TUR with datum points 4,2,2			Uncertainty and TUR with datum points 4,4,4		
	P/T (%)	Bias(X and Y) (μm)		2σ (μm)	Bias(X and Y) (μm)	
6	10.93	20.9	8.2	5.96	21.6	9.6
16	7.68	23.1	8.6	4.725	22.2	8.7
30	6.24	23.2	8.1	4.36	22.0	8.0

TABLE 14: P/T and Bias of Aluminum block

# of points	Uncertainty and TUR with datum points 4,2,2			Uncertainty and TUR with datum points 4,4,4		
	P/T (%)	Bias(X and Y) (μm)		2σ (μm)	Bias(X and Y) (μm)	
6	8.07	65.1	0.5	4.89	64.3	0.9
16	3.72	66.0	0.7	3.75	64.2	1.0
30	1.05	67.1	0.1	1.02	64.1	1.4

In the above tables an unexpected large value of bias is found. This results in the unacceptable values for TUR. Note that the P/T metric gives values that appear reasonable.

5.6.3 Conclusions for Steel and Aluminum plates experiments

The steel and aluminum plates were used to calculate TUR and P/T to show how different factors – such as part material – can influence the results. After analyzing the data it was found the steel plate has a higher TUR than the aluminum plate both for size and position. These two results are sensible, as the steel has a coefficient of thermal expansion (CTE) closer to the CMM scales. For different numbers of points, the TUR of position tolerance does not change because this measurement is dominated by the bias. We also show that the TUR utilizes both the bias and precision, while the P/T is only using precision. For this reason, we need to separately check the accuracy (bias) using a reference value. Because this experiment was done with only one metrology tool, we are comparing the capability of measuring different part materials for different measurands.

The same type of measurement capability study could be used for the same part on different measurement tools.

5.7 Measurement capability analysis

TUR can be used for the inspection of the end products and the measurement capability of the metrology tools. It was discussed above how TUR can be used for end product's inspection. An example is given comparing the measurement capability of metrology tools.

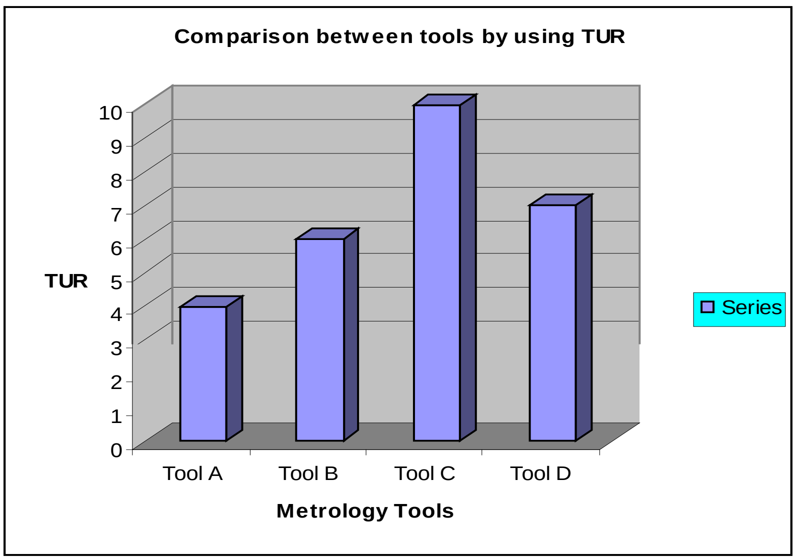


FIGURE 25: Measurement capability of metrology tools comparison

FIGURE 25 shows a graph where we can compare the measurement capability of four metrology tools. Tool C has the highest TUR value of 10. It means the measurement capability of this tool is better than the others. The measurement capabilities of other tools are ordered as follows Tool D, Tool B, and tool A. Comparing the P/T values for these tools reveals that Tool C will give smallest value, and then consequently Tool D, Tool B and tool A.

CHAPTER 6: TEST UNCERTAINTY

Measurements and measurement results have significant influence in many industrial sectors like trade, manufacturing companies, health services, safety, environmental protection, and others. In commercial transactions, the uncertainty of measurement results is important to decisions made between suppliers and customers. The uncertainty contributors need to be considered carefully to obtain a good estimate of the product quality. One of the uncertainty contributors is the measurement equipment, which naturally plays a key role in the measurement process. The uncertainty of calibrating the measuring instrument can be described as "test uncertainty." This uncertainty value is intended to capture “how well” the instrument errors are known, and thus the actual instrument errors are excluded. Contributors to the test uncertainty may include the uncertainty of the reference artifact used by the tester and details of the tester's measurement procedure that result in errors and uncertainty. It is often the case that the uncertainty from the artifact is small enough that it does not affect the test very much. For test uncertainty the "tester" is responsible when evaluating an instrument. Tester performance has a great influence on the test uncertainty results. Better performance by the tester can result in a smaller test uncertainty.

So the test uncertainty significantly depends on the influence of the human operator, test procedure (which should be well recognized) and reference artifact. When calculating the test uncertainty all these factors should be reasonably estimated to ensure that the result does not give any wrong impression of uncertainty. Most notably absent from the test uncertainty is the repeatability and resolution of the instrument under test. Test uncertainty is only the indication of the quality of the test; it is not the machine performance. By defining the test, how well the test is performed, the influence of the operator, selection and placement of test instrument; test uncertainty can be decreased and consequently, precision and usefulness of the test can be increased. Measurement uncertainty is a familiar topic in industry and discussed in chapter 2. In this chapter test uncertainty is discussed in detail.

6.1 Definitions

Some related terms of test uncertainty are defined from VIM.

Calibration

> Set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards.

A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.

It is necessary to verify the measuring instruments' performance through the calibration process which is a reliable source both for the suppliers and the clients. Many disputes occurred due to the lack of proper understanding of the calibration process. Sometimes products are accepted by the supplier but rejected from the customers. So the problem is usually solved by a third party, calibration service. Artifacts and reference standards can be considered as reliable reference values when certified by a calibration laboratory.

For test uncertainty, measurement instruments need to be calibrated by using the reference artifact. These calibrations can be done by the supplier, client, and calibration lab. Consequently, the different test uncertainty results can indicate comparisons between the testers' performance and the artifacts quality.

Calibration hierarchy

> It is the sequence of calibrations from a reference to the final measuring system, where the outcome of each calibration depends on the outcome of the previous calibration.

The elements of a calibration hierarchy are one or more measurement standards and measuring systems operated according to measurement procedures. For this definition, the 'reference' can be a definition of a measurement unit through its practical realization, or a measurement procedure, or a measurement standard. A comparison between two measurement standards may be viewed as a calibration if the comparison is used to check and, if necessary, correct the quantity value and measurement uncertainty attributed to one of the measurement standards.

All measuring instruments which are using in the different sectors of human life are connected with the national standard through a continuous chain of the calibration process. Calibration hierarchy is important for more reliability for the acceptance of a product.

As test uncertainty is a new concept, it is essential for its reliability to fulfill the criteria of the unbroken chain of the calibration process.

Metrological traceability

> It is the property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

For this definition, a ‘reference’ can be a definition of a measurement unit through its practical realization, or a measurement procedure including the measurement unit for a non-ordinal quantity, or a measurement standard. Metrological traceability requires an established calibration hierarchy. Specification of the reference must include the time at which this reference was used in establishing the calibration hierarchy, along with any other relevant metrological information about the reference, such as when the first calibration in the calibration hierarchy was performed. For measurements with more than one input quantity in the measurement model, each of the input quantity values should itself be metrological traceable and the calibration hierarchy involved may form a branched structure or a network. The effort involved in establishing metrological traceability for each input quantity value should be commensurate with its relative contribution to the measurement result. Metrological traceability of a measurement result does not ensure that the measurement uncertainty is adequate for a given purpose or that there is an absence of mistakes. A comparison between two measurement standards may be viewed as a calibration if the comparison is used to check and, if necessary, correct the quantity value and measurement uncertainty attributed to one of the measurement standards. The abbreviated term “traceability” is sometimes used to mean ‘metrological traceability’ as well as other concepts, such as ‘sample traceability’ or ‘document traceability’ or ‘instrument traceability’ or ‘material traceability’, where the history ("trace") of an item is meant. Therefore, the full term of "metrological traceability" is preferred if there is any risk of confusion.

Each contributor of test uncertainty needs to fulfill the criteria of metrological traceability for acceptability.

Metrological traceability chain

> Traceability chain is a sequence of measurement standards and calibrations that is used to relate a measurement result to a reference.

A metrological traceability chain is defined through a calibration hierarchy. A metrological traceability chain is used to establish metrological traceability of a measurement result. A comparison between two measurement standards may be viewed as a calibration if the comparison is used to check and, if necessary, correct the quantity value and measurement uncertainty attributed to one of the measurement standards.

Test uncertainty of any instrument needs to fulfill the criteria of the unbroken chain of metrological traceability.

6.2 Contributors of test uncertainty

The contributors of test uncertainty are those which are associated when testing an instrument. Test uncertainty included the uncertainty contribution from both the person who is doing the test (the tester) and the reference artifact (test equipment) which the person is using to do the test. ISO/TS 23165 describes any error introduced by the instrument should not be included in test uncertainty, so the uncertainty from instrument is not included in test uncertainty. Two examples of estimating test uncertainty are explained; the calibration of a CMM and the calibration of a micrometer.

6.2.1 Test uncertainty contributors for CMM

The CMM is calibrated by using a step gage. This is shown in FIGURE 26.

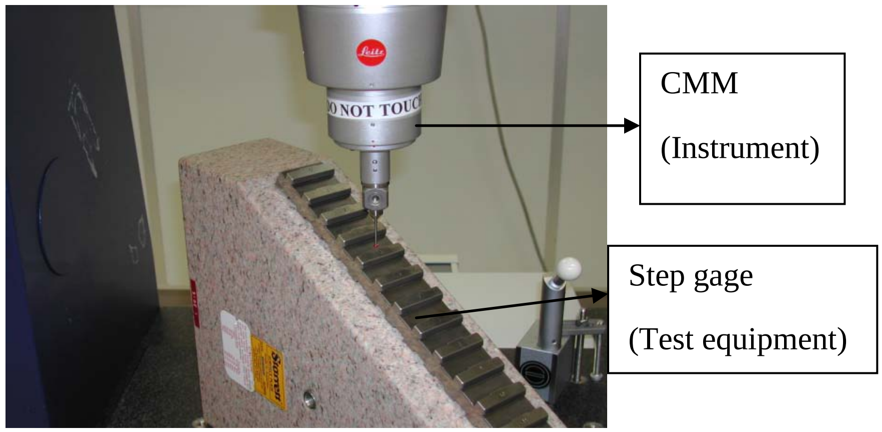


FIGURE 26: CMM calibration using a step gage

When the CMM is calibrated by using a step gage the uncertainty sources are from the step gage (artifact), the CMM (Instrument), and the tester who is performing the test. The uncertainties are shown in FIGURE 27.

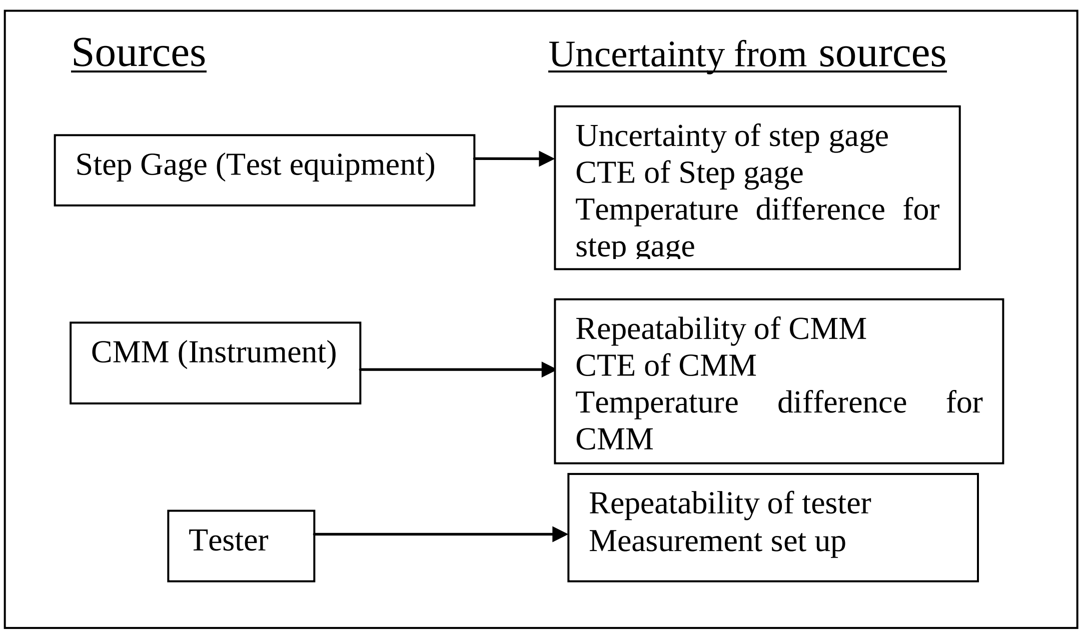


FIGURE 27: Sources of U in the calibration of CMM by using step gauge

It is important to find, from these sources what should be the components of test uncertainty. The uncertainty contributors from the instrument such as the repeatability of the CMM and the CTE of the CMM scales – should not be included in test uncertainty.

These are attributes of the instrument that is being tested, not the quality of the test. It is important to check the specification of the instrument in the case of uncertainty due to temperature. When temperature is maintained within the specification, it should not be included in test uncertainty. In the above example temperature was within the limit, the uncertainty due to the temperature of CMM and the step gage should not be included in test uncertainty. If temperature is not maintained within the specification uncertainty from temperature should be included in test uncertainty. Other sources of uncertainty from the step gage and tester like repeatability, fixturing, and cleaning which are the tester's responsibilities should be included in test uncertainty. The contributors of test uncertainty are shown in FIGURE 28.

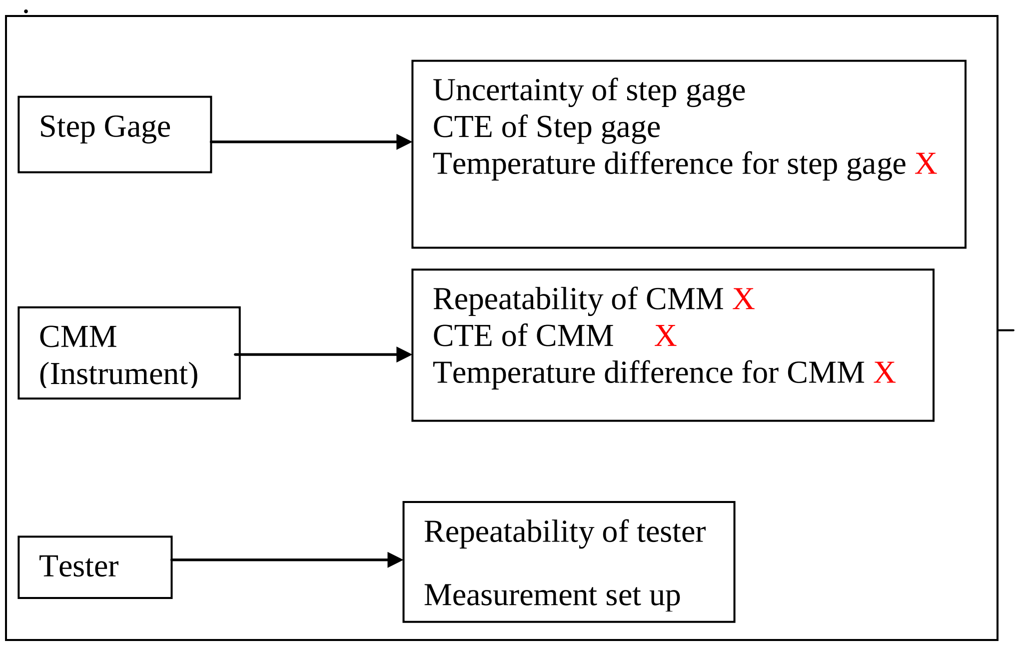


FIGURE 28: Sources of test U.in the calibration of CMM by using step gauge

Test uncertainty when calibrating the CMM by using step gage is shown in FIGURE 29.

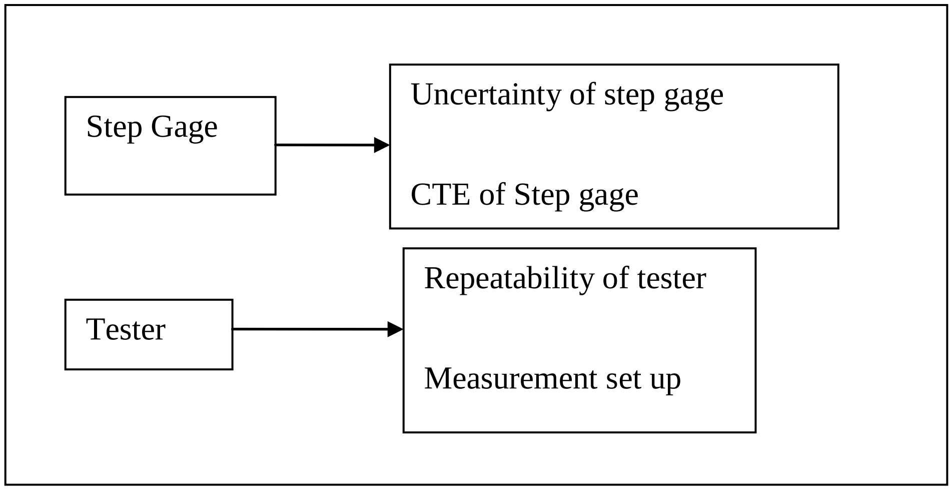


FIGURE 29: Sources of test U in the calibration of CMM by using step gage

The value of test uncertainty is smaller than the measurement uncertainty (some sources of uncertainty are not included in test uncertainty) and is not any fixed value. The performance of the tester during the test may be the main source of error and it may vary in different tests.

6.2.2 Test uncertainty contributor for micrometer and gage block

Test uncertainty is explained for calibrating a micrometer using the gage block and calibrating the gage block by using a micrometer. The same environmental condition was maintained and the same data will be analyzed both for the micrometer and gage block. The micrometer and gage blocks are shown in FIGURE 30 and FIGURE 31.

FIGURE 30: Micrometer

FIGURE 31: Gage block

When calibrating the micrometer by using the gage block, the uncertainty sources are the gage block (artifact), micrometer (Instrument), temperature (Environment), and tester. The uncertainty sources are shown in FIGURE 32.

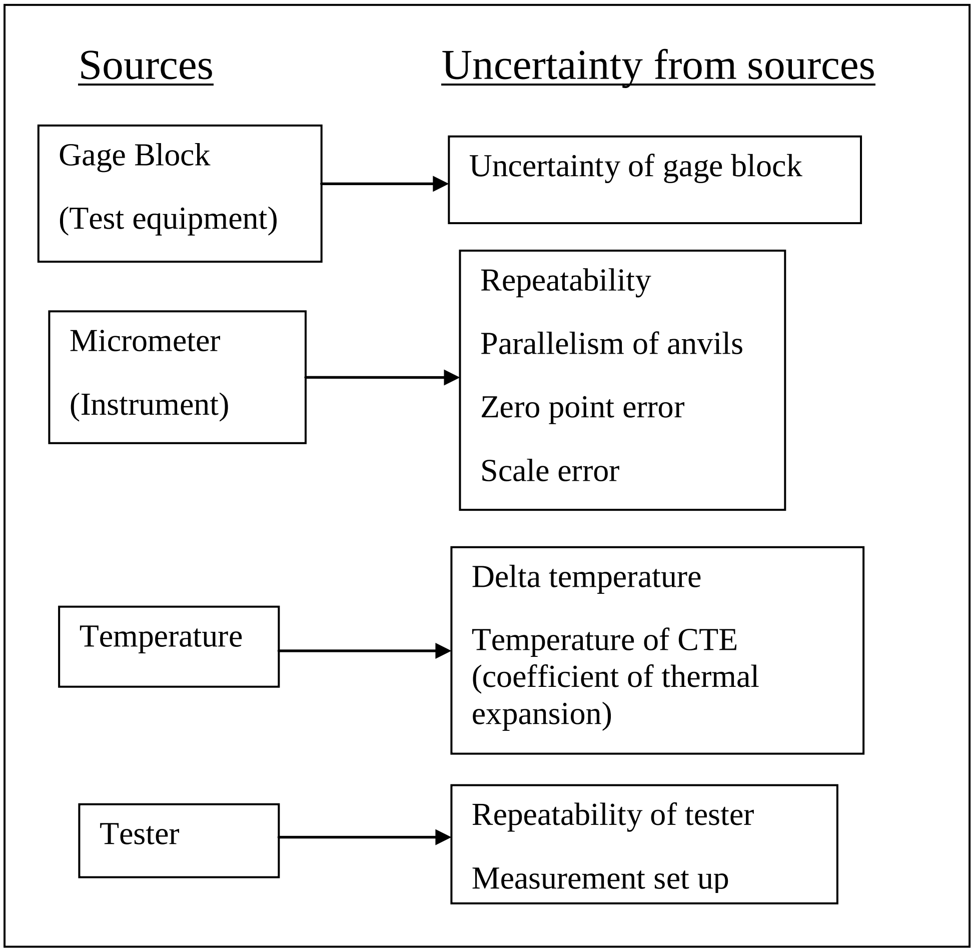


FIGURE 32: Sources of U in the calibration of micrometer by using gage block

The task is to calibrate the micrometer by using the gage block; uncertainty from the micrometer should not be included in the test uncertainty budget as mentioned earlier from ISO/TS 23165. The gage block is used to calibrate the micrometer so the uncertainty due to gage block should be included in test uncertainty budget. Another important source is uncertainty due to the tester. In test uncertainty one should always include this factor. For calibration of the micrometer the specification states that temperature should be maintained at 20^0C during calibration. It is the tester's responsibility to maintain this temperature. As the temperature was not maintained at 20^0C in this experiment, any error introduced from temperature should be included in test uncertainty budget. If it is mentioned in the specification, temperature during the experiment can be maintained in a specific range like 18^0C to 22^0C and it is maintained by the tester then it should not be included in test uncertainty budget. The sources of test uncertainty for calibration of micrometer by using gage blocks are shown in FIGURE 33.

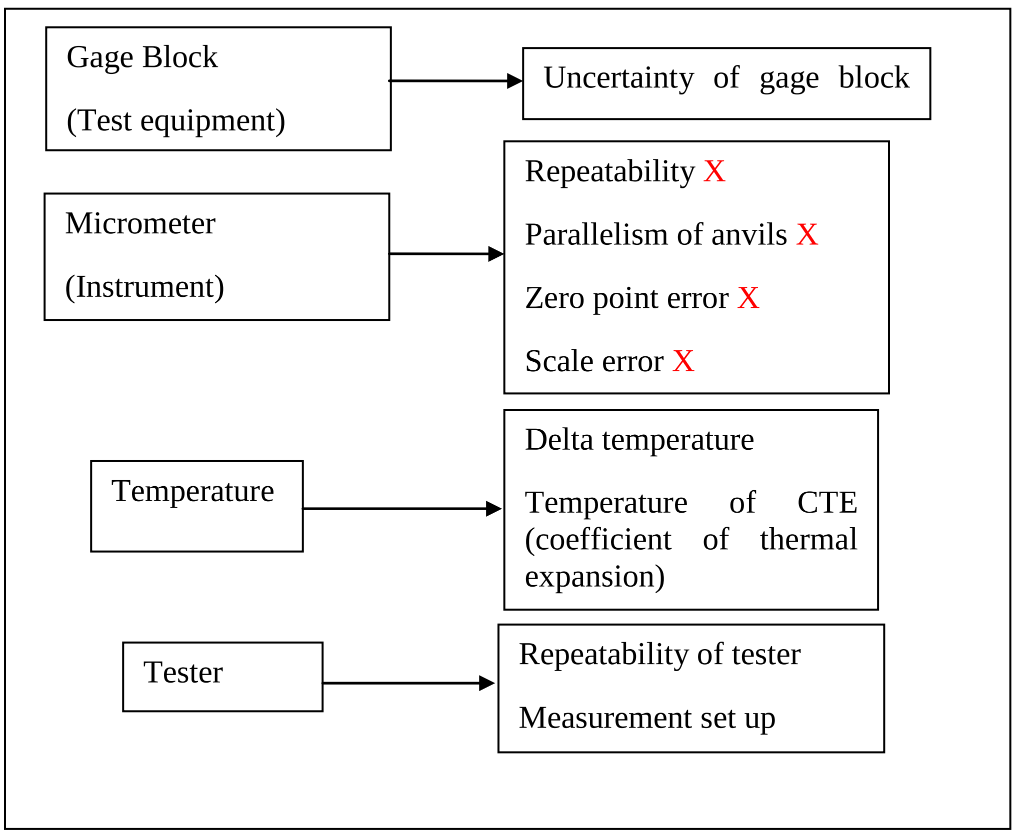


FIGURE 33: Sources of test U in the calibration micrometer by using gage block

The task is to calibrate the gage block by using a micrometer - uncertainty from the gage block (instrument) should not be included in the test uncertainty budget. The micrometer is used to calibrate the gage block so the uncertainty due to micrometer should be included in the test uncertainty budget. The temperature was not maintained at 20^0C during calibration so it should be included in test uncertainty budget here. The sources of test uncertainty when calibrating a gage block by using the micrometer are shown in FIGURE 34.

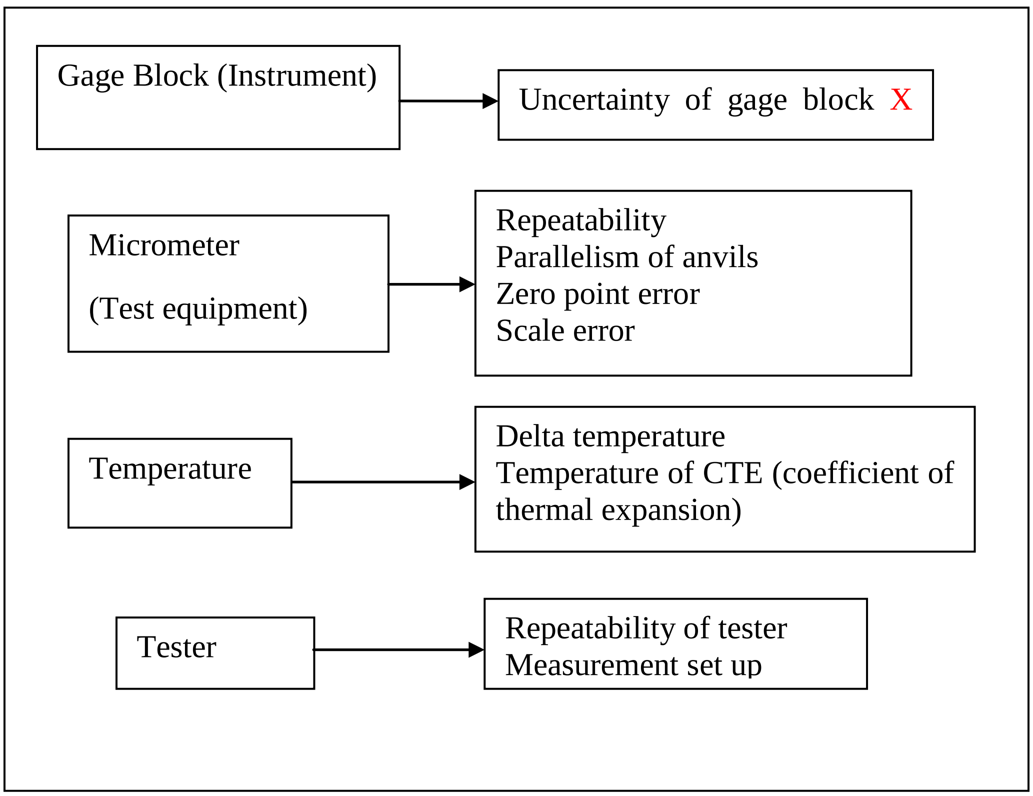


FIGURE 34: Sources of test uncertainty when calibrating gage block

From the above discussion it is found for the same experiment the test uncertainty value may be different depending on the type of calibration. In TABLE 15 is shown the test uncertainty budget both for micrometer and gage block. The test uncertainty for micrometer calibration is 12.21 µin and gage block calibration is 11.85 µin. These values are different because the calibration type was different though it was for same experiment.

TABLE 15: Uncertainty Budget

Source	Evaluation type	Distribution type	Standard U (uin)	Test Uof micrometer (uin)	Test U of gage block (uin)
Gage block	B	Rectangular	2.32	2.32	
Repeatability	A	Normal	0.29		0.29
Scale error	B	Rectangular	1.16		1.16
Zero point error	B	Rectangular	1.16		1.16
Parallelism of anvil	B	Rectangular	2.9		2.9
Delta Temp	B	U-shape	4.08	4.08	4.08
U due to CTE	B	U-shape	3.91	3.91	3.91
		Combined Uncertainty,Uc	6.96	6.10	5.92
		Expanded Uncertainty,	13.93	12.21	11.85

6.3 Comparison between test U, calibration and task specific U

To understand test uncertainty clearly, it is compared with the calibration and task specific uncertainty from two points of view. The first aspect is the measurand. It is known, there are different kinds of measurands for different kinds of measurement processes. Consequently the Uncertainty will be different also. A clear description of different kinds of Uncertainty associated with different kinds of measurands is explained in TABLE 16. Here one new term, calibration uncertainty, is introduced. It can be explained from S.D Phillips et al paper where it states, “The relationship between the measured or indicated values and those of the reference values is a key issue with regards to calibration…all calibration must include the statement about the accuracy of the instrument or artifact as required by traceability.” This can be interpreted to mean calibration uncertainty, in this discussion. Any calibration result showing the error or the deviation of the measurand with respect to the reference value and uncertainty associated with this error can be named as calibration uncertainty. The second aspect of comparison is with respect to contributors of uncertainty which are shown in TABLE 17.

TABLE 16: Measurand for different kinds of uncertainty

Measurand / Quantity	Activity	Uncertainty	Rules
Some characteristic of the work piece	Measuring a work piece to conform to specific value or tolerance	Task specific Uncertainty	TUR
The length of the artifact	Calibrating the material standard size. (diameter of a Sphere), length of a gage block etc.	Calibration Uncertainty	TUR
The error of the instrument (E-value)	Calibrating an instrument	Test Uncertainty	Cm

TABLE 17: Uncertainty contributors for different kinds of uncertainty

Contributor	Task Specific Uncertainty	Calibration Uncertainty	Test Uncertainty
Environment 1)Temperature 2)Work Piece	1) If instrument does not compensate with temperature it has effect on TSU 2) The temperature difference between W/P and room temp.	1) Measurement of instrument scale temperature-like temperature diff., average temp. 2) The temperature difference between W/P and room temp.	1) Any error introduced by the instrument is not the part of TU, 2) If artifact is compensate with temperature of instrument, then it is part of instrument, not include in TU
Reference element of measurement equipment	Resolution of the main scale (analogue or digital)	Scale error of the micrometer	Does not apply (Part of the instrument)

TABLE 17 (continued)

Measurement equipment	Zero-point stability Parallaxes	Zero point error, Parallelism of anvils	Does not apply (Part of the instrument)
Measurement setup (Probe selection, tip size etc.)	Form deviation of tip, offset, extension	Usually optimized or specified	Usually specified by std. Poor setup may influence TU.
Software and calculations	Rounding, SamplingAlgorithms, Quantification	Well defined in the standard, may be eliminated	Well defined in the standard, may be eliminated
Metrologist	Experience, training, knowledge	Reproducibility	Reproducibility
Measurement object , work piece or measuring instrument characteristics	Surface roughness, form deviation of the w/p	Form error of gage block, uncertainty of the length of gage block	Form error of artifact, uncertainty for the length of artifact
Definition of the GPS Characteristic, w/p or measuring instrument characteristic	Datum, reference system	Datum, reference system	Datum, Coordinate system
Measuring procedure	Alignment, Clamping fixturing, Number of measurement etc. example: Due to the measurement process of w/p like repeatability	Physical and software alignment, Clamping fixturing, number of measurement etc. example: Due to the measurement process of gauge block like repeatability	Alignment, Clamping fixturing, number of measurement etc. example: Instrument repeatability error is not the part of TU, but the repeatability error for tester is the part of TU.

6.4 Comparison of CMM testing data

Three different methods have been used to compare the results for CMM testing. These are

1. Simulation using PUNDIT™
2. Actual testing to ISO 10360-2
3. Calculation using ISO TS 23165

These experiments were done by the instruction of ISO10360-2. It is mentioned, in this standard for CMM testing, which is necessary to find the error of indication for size measurement (E- value). This value should not exceed the maximum permissible error, MPE_E, as stated by the manufacturer. FIGURE 35 and FIGURE 36 are shown the experimental set up for this test.

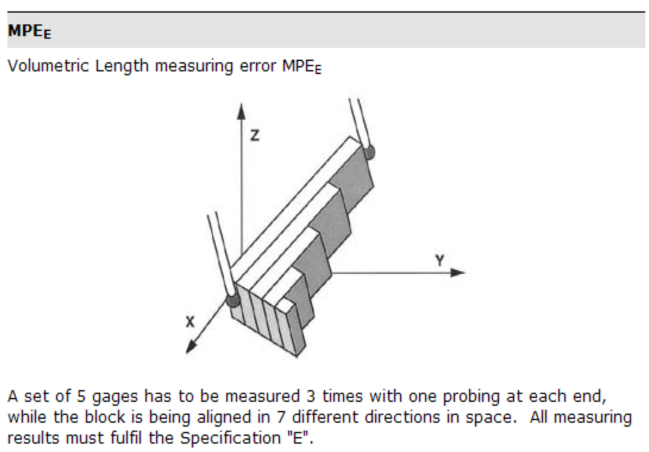


FIGURE 35: E-test [21]

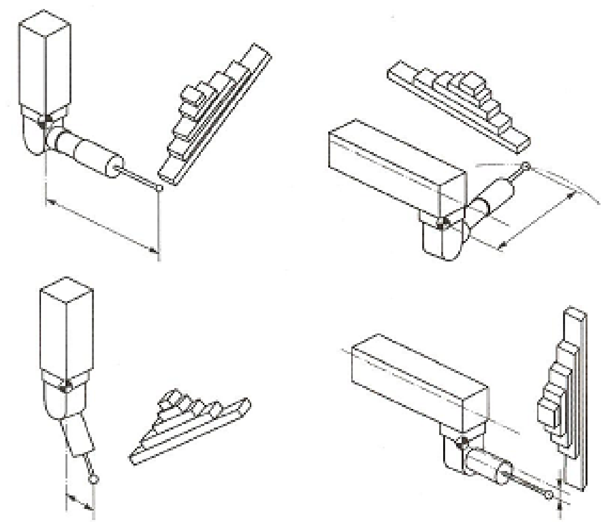


FIGURE 36: E-test [10360-2]

6.4.1 Simulation using PUNDIT

To evaluate uncertainty of the CMM, different simulations have been done by using PUNDIT. It is useful because it gives an estimation of the uncertainty before the actual testing. The blocks (as defined in the ISO standard) were modeled in PUNDIT which is shown in FIGURE 37.

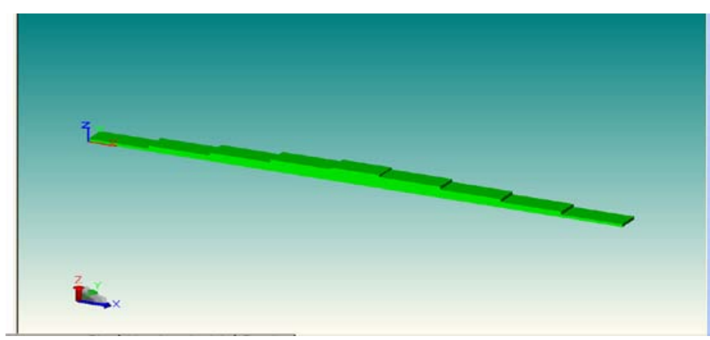


FIGURE 37: Artifact with 5 test lengths (as used in ISO testing)

There were two sampling methods used in the simulation which are shown in FIGURE 38 and FIGURE 39. Initially four numbers of points were taken on each side shown in FIGURE 38 . In the second measurement plan one point was taken on each side in the middle of the plane shown in FIGURE 39.

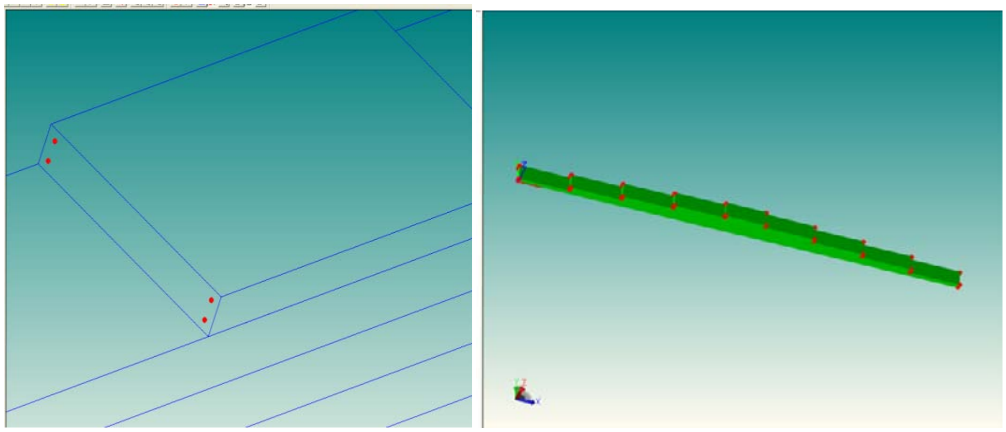


FIGURE 38: Initial measurement schemes

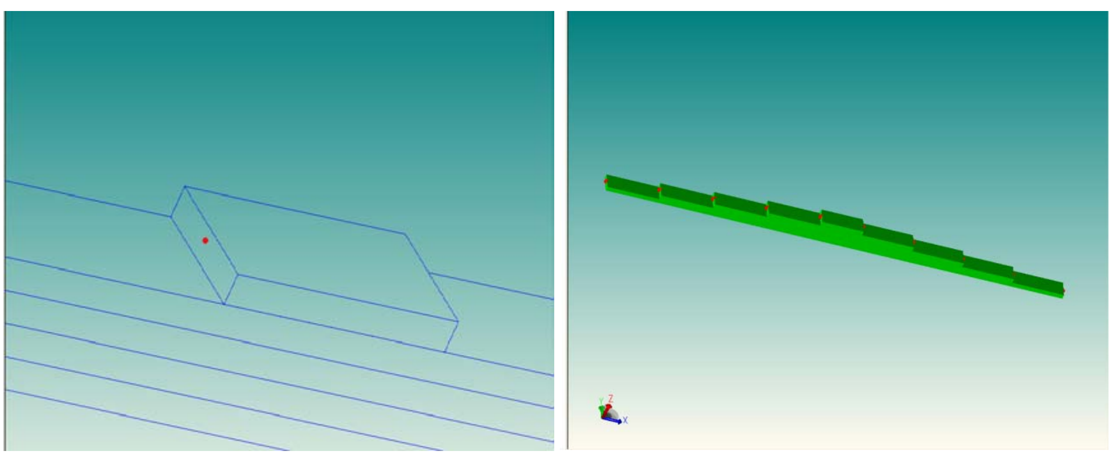
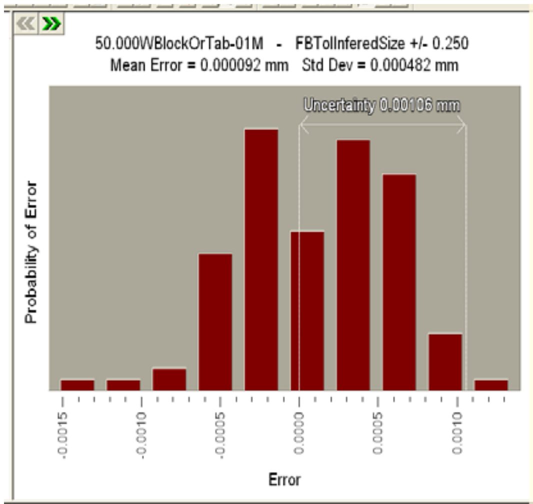
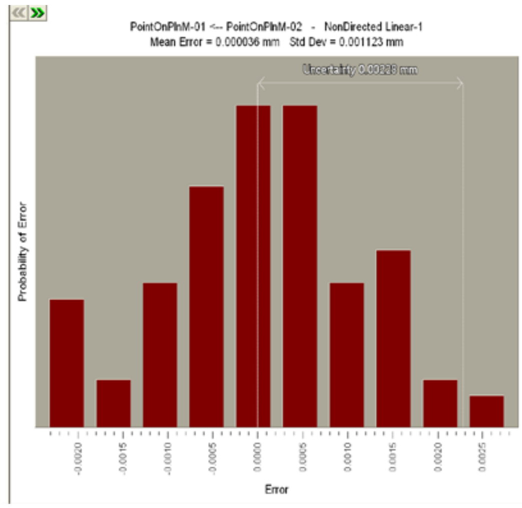


FIGURE 39: Single point probing scheme



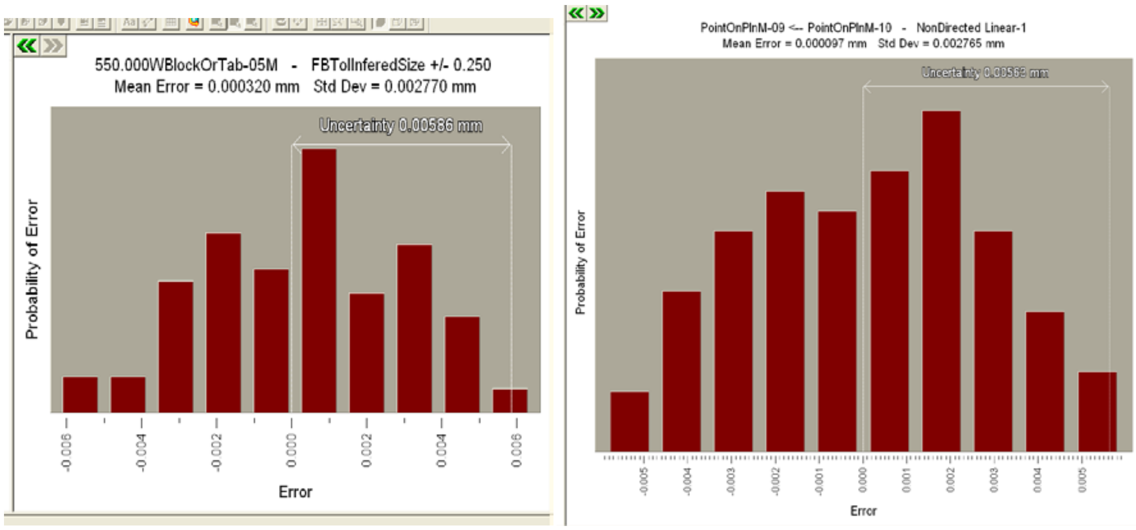


Test Length = 50mm

4 points/end: U = .00106mm 1 point/end: U = .00228mm

FIGURE 40: Simulation results (1)

Test results for the top block with test length 50 mm are shown in FIGURE 40. It is found from the results that the uncertainty for 4 points is giving lower uncertainty than the 1 point case. Test results for the longest block with test length 550 mm are shown in FIGURE 41. It is found from the results that the uncertainty for the 4 point and the 1 point data do not differ significantly. This may be due to the long length of the block. For the comparison with other methods the largest value of the uncertainty was taken from all of these results.



Test Length = 550mm

4 points/end: U = .00586mm 1 point/end: U = .00563mm

FIGURE 41: Simulation results (2)

Practical experiments have been done for CMM testing in 20 different positions to find the E-value, shown in FIGURE 42. Some experimental set ups are shown in FIGURE 43 and FIGURE 44 . The offset probe schematic and set up, mentioned in the standard for CMM testing are shown in FIGURE 45 and FIGURE 46.

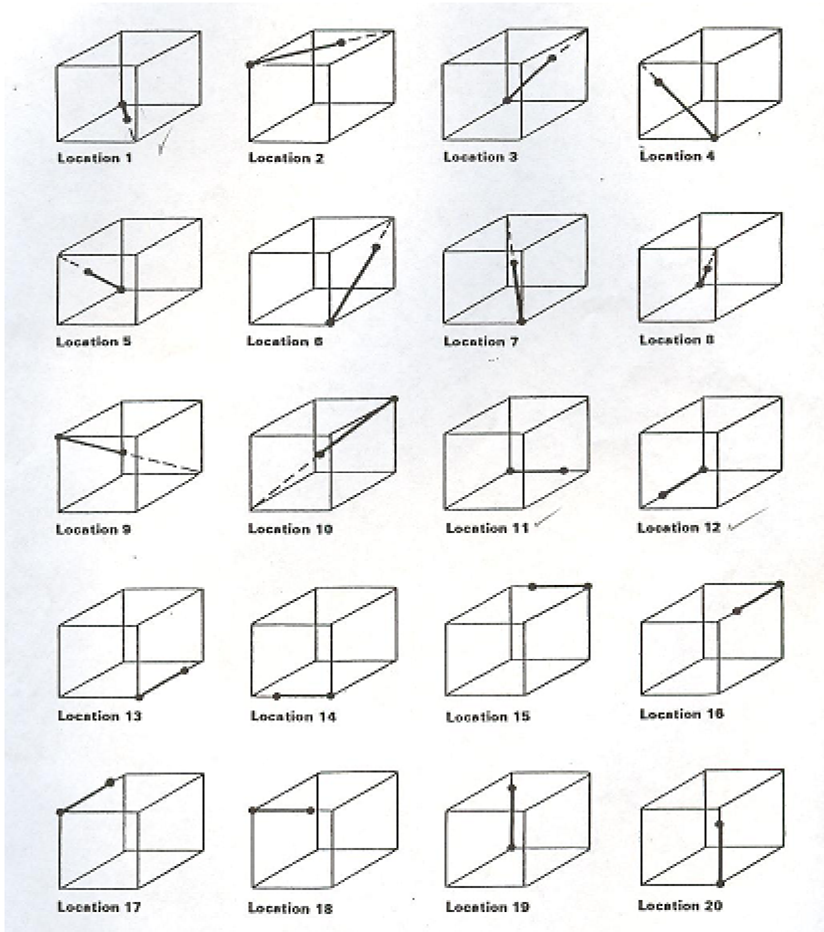


FIGURE 42: different positions [B89.4.]

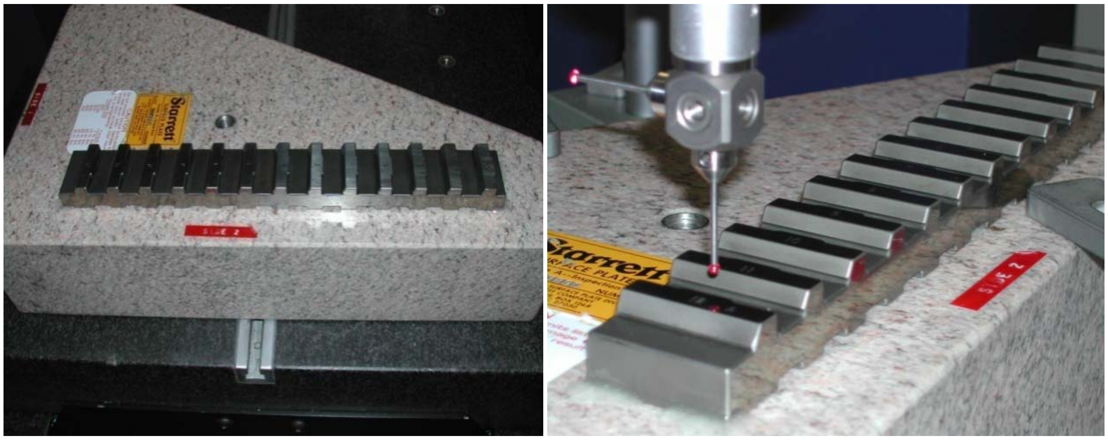


FIGURE 43: Y-linear

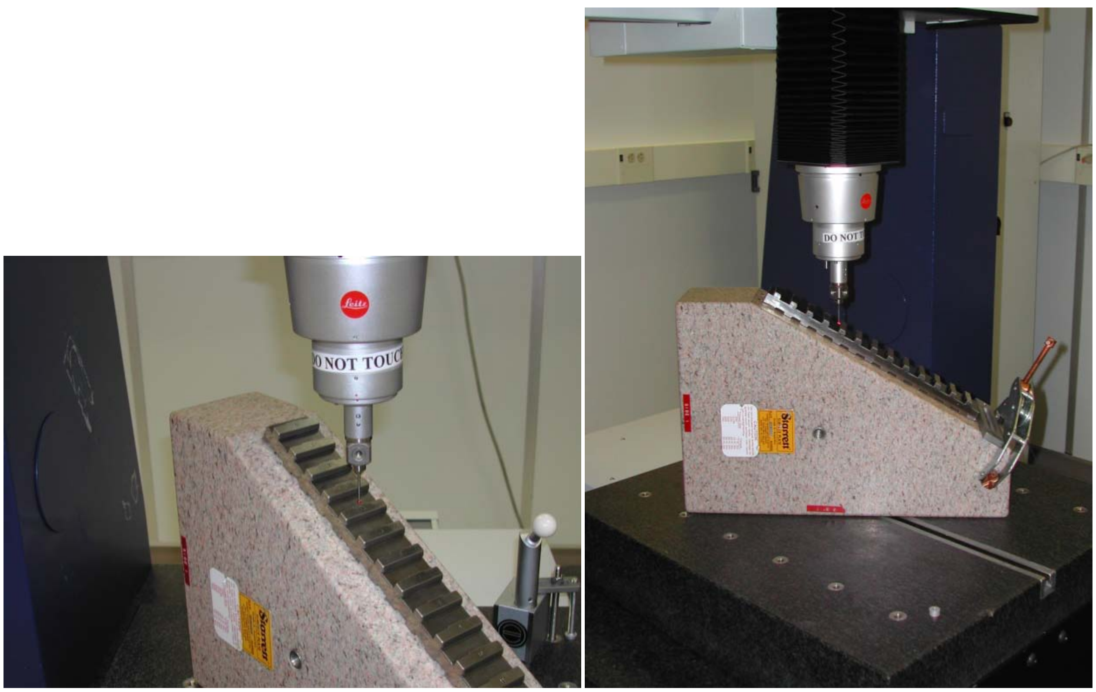


FIGURE 44: Diagonal position

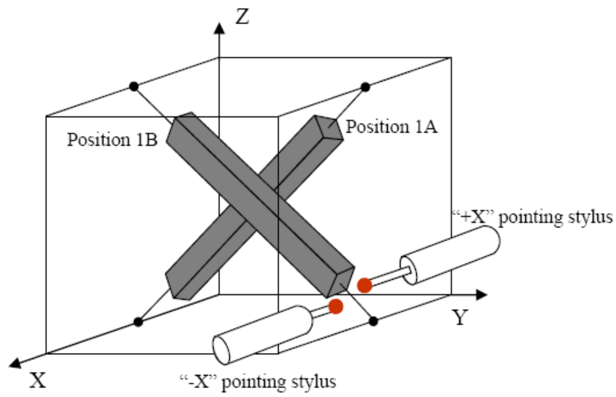


FIGURE 45: Schematic of offset length test

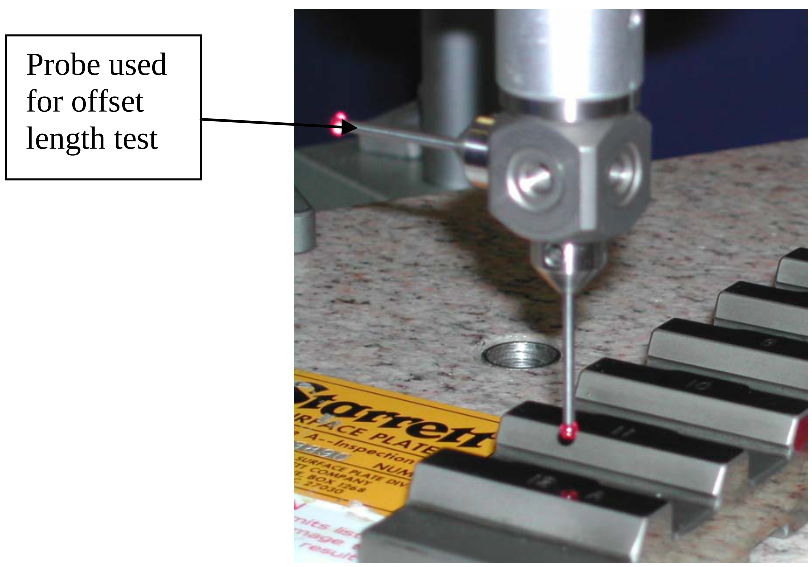


FIGURE 46: Off set probe

6.4.2 Experiment results

Experiments were done two times. The experimental results are shown in FIGURE 47, FIGURE 48, FIGURE 49. Measurement round 1 is represented by the diamond shape and round 2 by the rectangle shape. The results for X-linear (measured parallel to X-axis) from FIGURE 47 are 0.00027 mm (round 1) and 0.00031 mm (round 2), for diagonal (measured diagonally to the CMM axes) from FIGURE 48 FIGURE 48 are 0.00165mm (round 1) and 0.0017 mm (round2), and for the offset probe test from FIGURE 49 is 0.0035mm (round 1 and round 2). The maximum error (E-value) from all of this is 0.0035 mm.

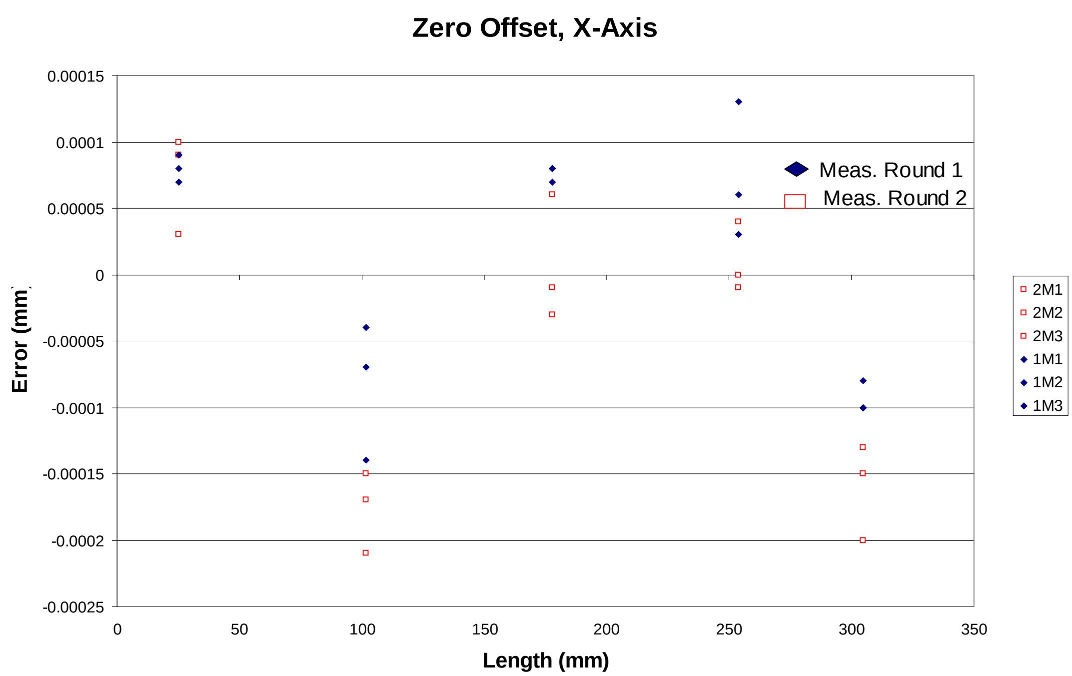


FIGURE 47: Results: X-axis Linear

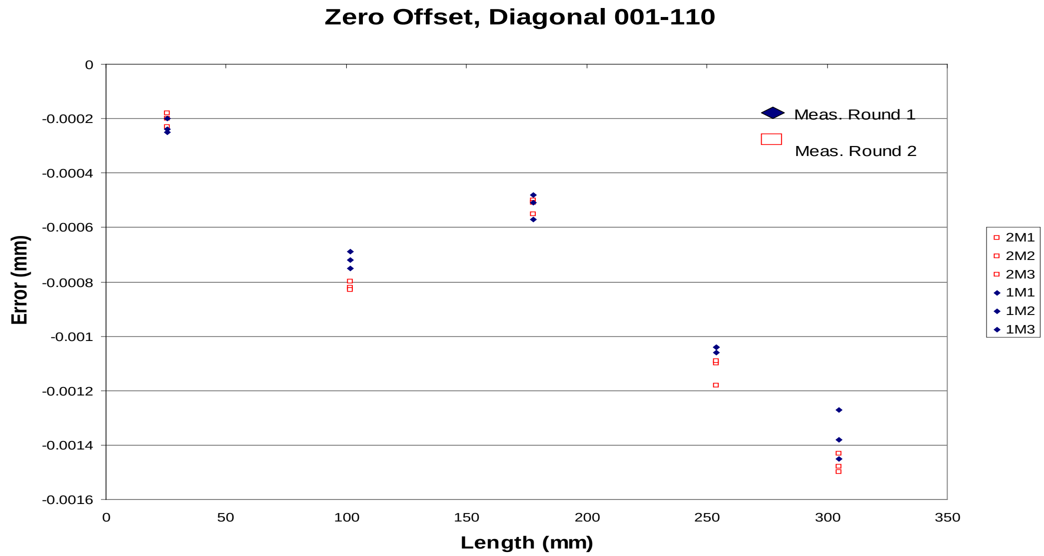


FIGURE 48: Results: Diagonal measurement

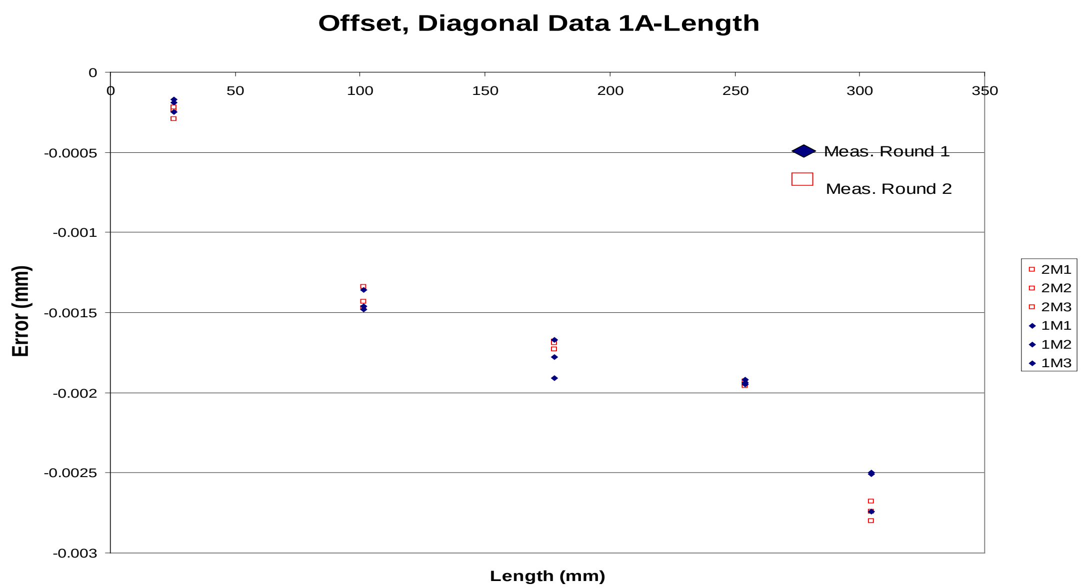


FIGURE 49: Results: Offset Probe Test

6.4.3 Test Uncertainty Calculation from ISO/TS 23165

The recommended equation for the standard uncertainty of the error is

$$U(E) = \sqrt{u^2(\varepsilon_{cal}) + u^2(\varepsilon_{\alpha}) + u^2(\varepsilon_{t}) + u^2(\varepsilon_{align}) + u^2(\varepsilon_{fixt})}$$

ε_{cal} Is the calibration of the material standard of size

ε_α Is the error due to in the input value of the CTE α of the material standard of size

ε_t Is the errors due to in the input value of the temperature of the material standard of size

ε_{align} Is the errors due to misalignment of the material standard of size

ε_{fixt} Is errors due to fixturing the material standard of size

Assuming some realistic values which are for all these parameters given in APPENDIX C and using in the above equation the value of uncertainty,

U (E) =.000112mm.

Results from three methods are shown in TABLE 18.

TABLE 18: Uncertainty from three methods

Simulation using PUNDIT^{TM}	Actual testing to ISO 10360-2	Calculation using ISO TS 23165
.00563mm	.0035mm	.000539mm

From the results, it is found that the uncertainty value when calculating by using the ISO/TS 23165 equation is smaller than the actual (ISO 10360-2) and the PUNDIT result. It is expected that the theoretical results should be smaller than the practical results because many uncertainty contributors are not present there. In actual testing, the environment was carefully maintained as specified by the manufacturer, but in the case of PUNDIT, some error may have been introduced which influenced the result. The test uncertainty value could not be found directly from these results. These results are the standard uncertainty which includes all the sources of uncertainty like tester, instrument, and artifact.

6.5 Ball bar test

Two different methods have been used to find the volumetric performance of CMM.

1. Actual testing to B89.4
2. Simulation using PUNDIT^{TM}
3. Calculation using ISO TS 23165

6.5.1 Actual testing by following B89.4

Actual tests have been done to find the volumetric performance of the CMM followed by standard B89.4. Four positions of experimental setups out of 20 total different positions (FIGURE 42) are shown in FIGURE 50.

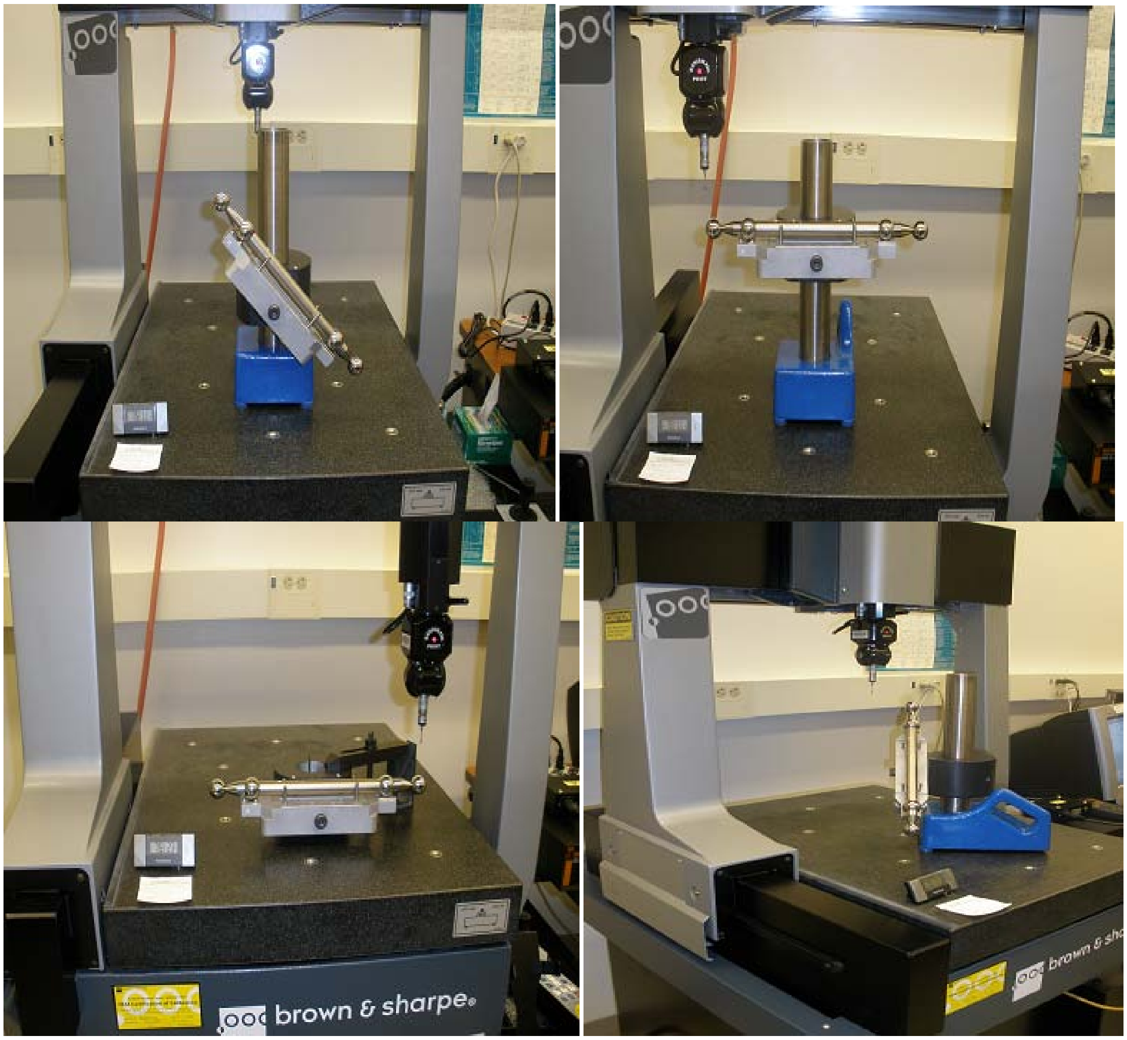


FIGURE 50: Experimental set up

Ball bar test results

The results of ball bar test are shown in FIGURE 51. The working tolerance is 13 um. This result includes uncertainty from all sources (CMM, tester, ball bar, and environment) of this experiment. Here test uncertainty could not be found directly.

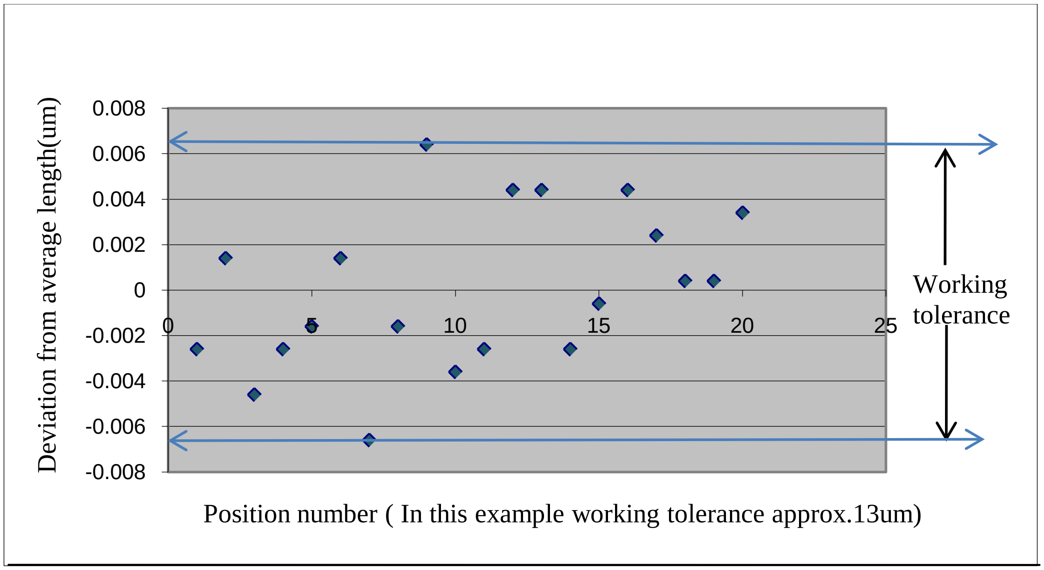


FIGURE 51: Ball bar test result

Ball bar test by using PUNDIT software

Simulations have been done by using the software PUNDIT to find the volumetric performance of the CMM. All of the inputs like environmental condition, CMM specification, ball bar's specification, and other factors reflected the actual experiment. The ball bar model and four positions from the 20 different positions of the volumetric performance test are shown in FIGURE 52 and FIGURE 53.

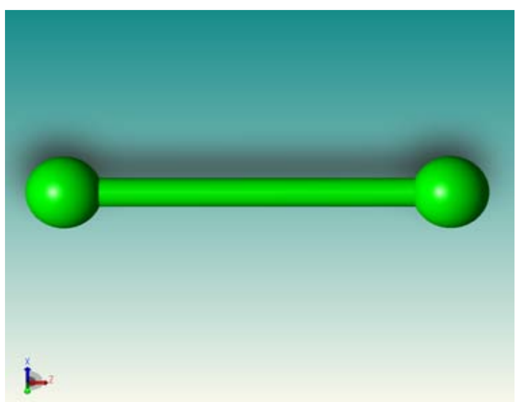


FIGURE 52: Ball bar

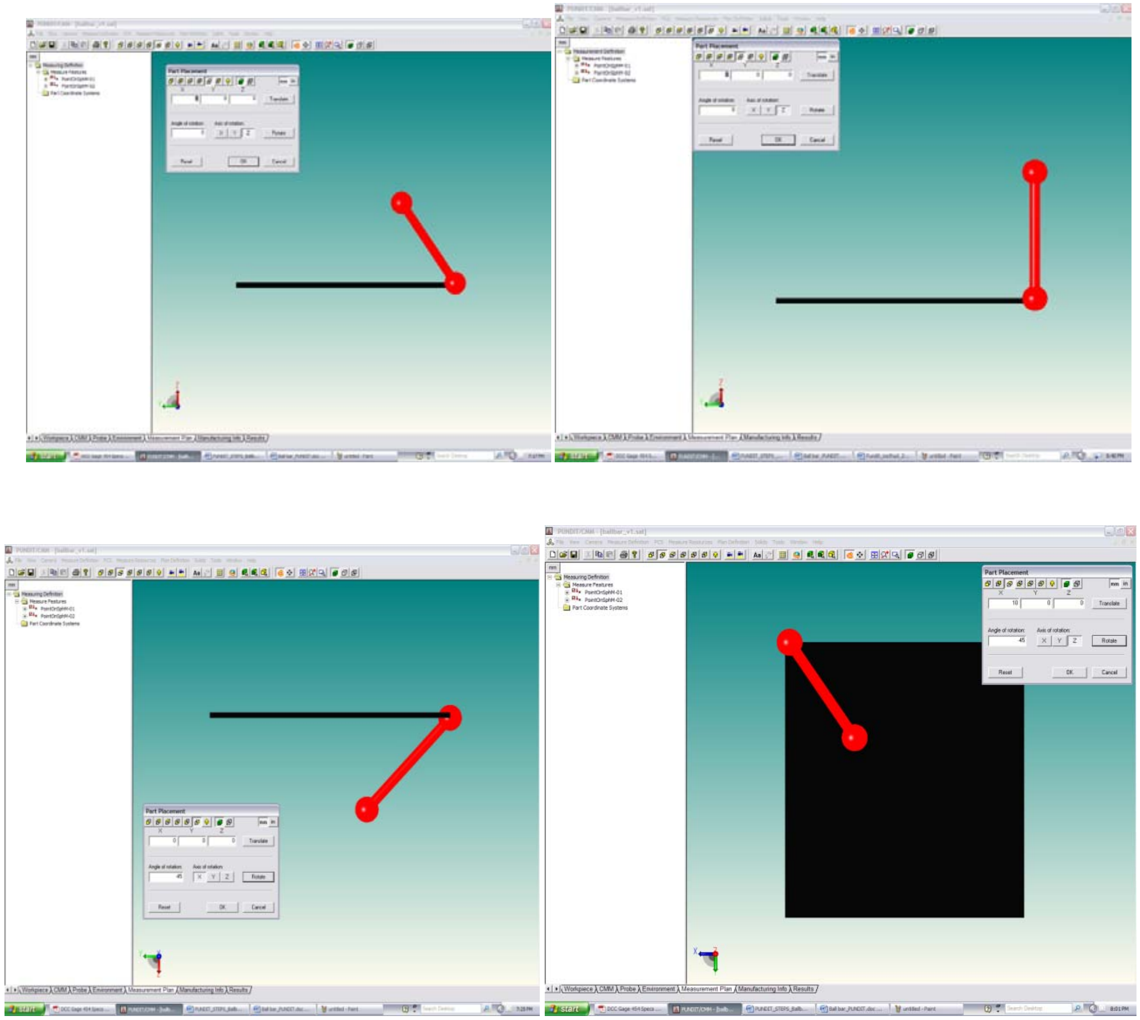


FIGURE 53: Ball bar set up by PUNDIT

One simulation result is shown in FIGURE 54. The standard deviation and mean can be found from these results.

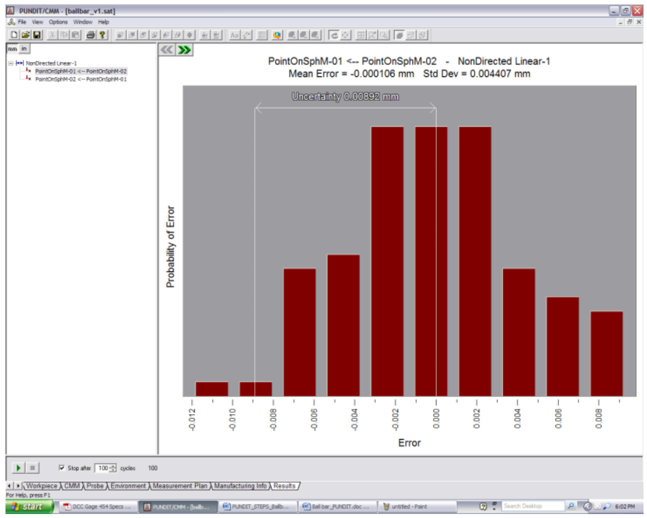


FIGURE 54: Simulation result

The maximum working tolerance was calculated using PUNDIT results in MATLAB. In MATLAB random numbers were added to the standard deviations found from PUNDIT. These data were added with the mean found from PUNDIT and the range was calculated. The result for the range was 7.856 were µm. Calculation using ISO TS 23165 are discussed in APPENDIX C.

TABLE 19: Comparison of ball bar test result from three methods

Simulation using PUNDIT™	Actual testing to B89.4	Calculation using ISO TS 23165
7.856um	13um	0.202 um

The simulation result is giving a smaller value than the actual test as expected. In the simulation, the 20 positions of the ball bar were theoretically perfect, whereas in the actual test they were not. Practical experiment involves more uncertainty contributors than simulation. Consequently actual test results were larger than PUNDIT results.

6.5.2 Ball bar test results with time

The ball bar test results are shown in FIGURE 55. The tester's performance with respect to time is improved; consequently it influences the test result. So the test uncertainty result in every test may be changed depending on the tester's capacity to perform the test. It is shown in FIGURE 56.

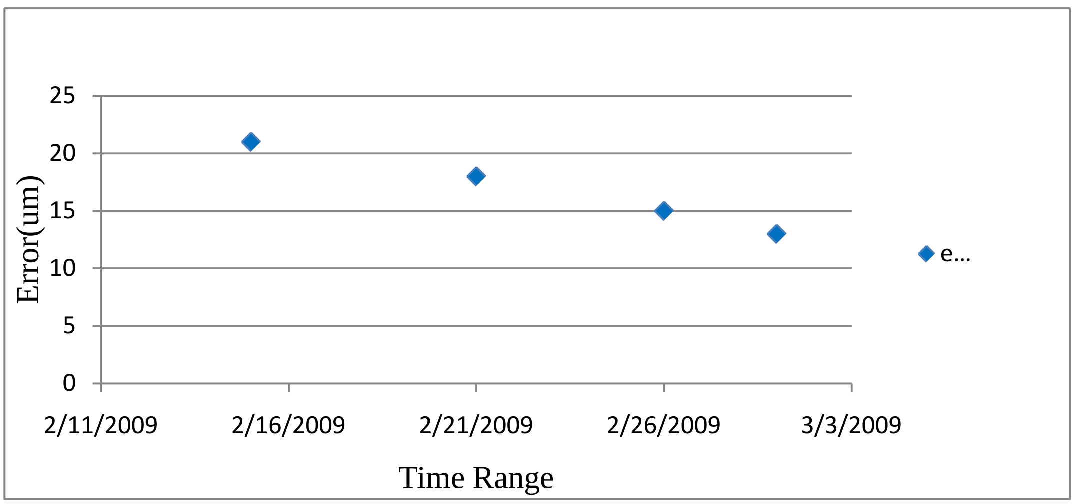


FIGURE 55: Test results improving with time

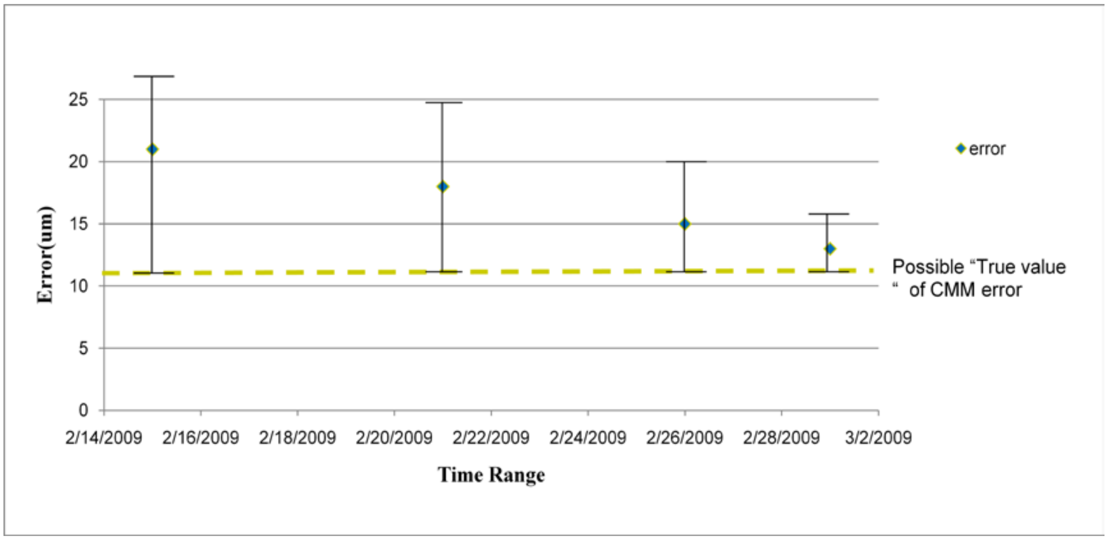


FIGURE 56: Test uncertainty value decreasing with time

6.5.3 Probe test

This test was done to find the probe error of the instrument. The probe is part of the CMM; any error from the probe indicates CMM error. FIGURE 57 and FIGURE 58 show the experimental set up for this test.

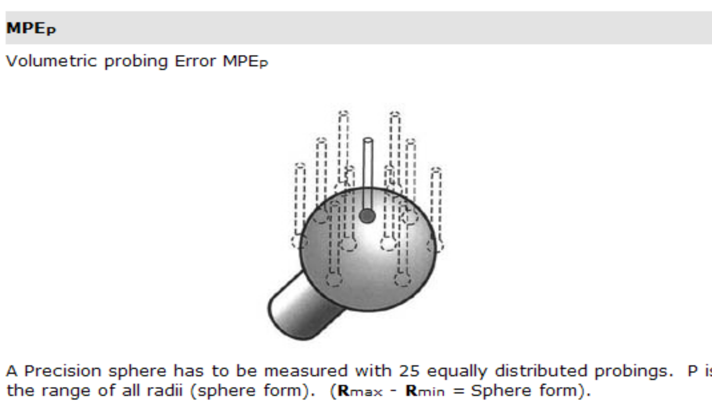


FIGURE 57: “P” Test

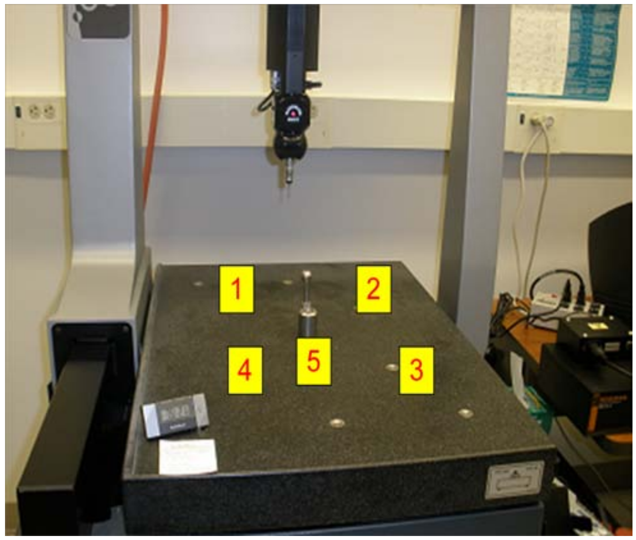


FIGURE 58: Experimental set up for probe test

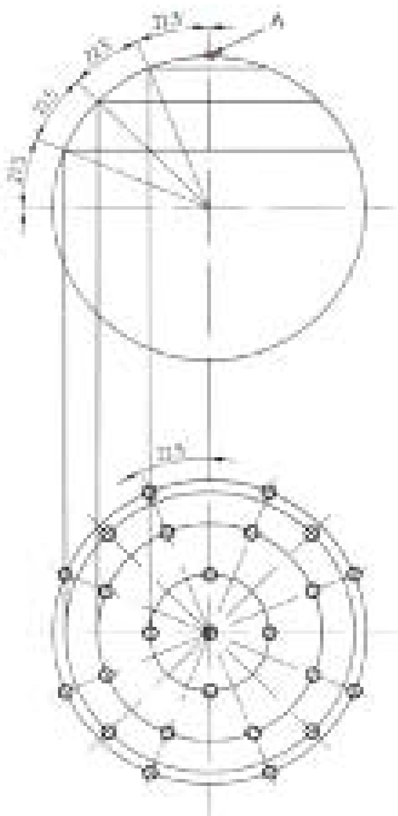


FIGURE 59: Target contact points [ISO10360-5]

The probe tests have been done for five different locations, shown in FIGURE 58. The probe test results for two different probes lengths, 20mm and 50 mm are shown in TABLE 20.

TABLE 20: Probe test results

Location	Probe with 20mm. length (μm)	Probe with 50mm. length (μm)
1	3	5
2	3	5
3	3	5
4	3	6
5	4	6

From the above results, it is found for the probe with 20mm length (which probe was using in this experiment) the maximum error value is 4 um. The probe is part of the CMM; error from the probe should not be included in the contributors of test uncertainty. The working tolerance from the ball bar test was 13 um, which includes the probe error of 4μm. From the above table it is found, that the probe error for the 50mm length probe is 6 μm. Result may vary using different probes. The probe test was done to give a demonstration of what error may be introduced from the instrument itself.

6.6 Conclusion

To calibrate measuring equipment like the CMM, certainly the tester's proficiency will have a large influence on the results. Different operators will yield different test results. If the tester is experienced or well trained, the test uncertainty result will be better (smaller) compared to that of an inexperienced tester. When doing experimental determination and verification, test uncertainty exist in the test, it is difficult to remove test uncertainty from the test.

CHAPTER 7: CONCLUSIONS AND FUTURE WORK

This chapter reviews the objectives, summarizes the conclusions, and looks at extensions for future work. One of the goals of this project was to develop a guideline on how to use TUR in industry to find the measurement capability of measuring tools and end products. This work was supported by an opportunity to do internship at INTEL. During this internship, one main task was to implement TUR and compare their own metrics to find the measurement capability of the measuring tools. These were first compared with the three reference tools: Wyko (Scanning White Light Interferometer, or SWLI), Zygo (SWLI) & Keyence (Confocal). For this comparisons was necessary to create a "pseudo-bump" standard, as no standards exist for that measurement. Second comparison was between the high volume measurement (HVM) tools Solvision (Moiré fringe projection), Nikon (Confocal), ICOS (Confocal) which are used for the measurement of the end products. It is found that both for the reference and HVM tools, TUR and INTEL metric gave the same results for the measurement capability of the metrology tools individually and also the capability between them. So TUR was successfully implemented to find the measurement capability of metrology tools. For TUR used in measuring end products different dimensions like length, true position of the hole, and diameter, could also be implemented as different experiments, simulations were done in this research by using different sampling and it could successfully find theses arrtibutes. So TUR is ready for use in the industry; they only need the measurement tool and the software or expertise to find the task specific uncertainty.

Test uncertainty is a new concept in the field of dimensional measurement. It is helpful in understanding instrument test criteria, for determining the confidence in machine conformance in the buying and selling measurement equipment, and in the calibration of this equipment. This research developed concepts to explain how it is different than the other uncertainty, and how one can calculate it. For this purpose many experiments have been done with micrometer and CMM. These experimental results were used to clarify when one instrument is tested, which factors influence the results. The tester who is performing the test was shown to often have the greatest influence on the test, and next the artifact or equipment that is using for this testing. The specification is also very important for this testing. It should be testers' responsibility to maintain the conditions of the test. The development of these concepts was found from this research.

7.1 Future work

There are two additional subject areas open to further work, and hopefully there will be progress in these areas, with the help of the experts in the standards community. The first project is to find meaningful and consistent language to describe this quantity (referred to here as test uncertainty) and to standardize a consistent vocabulary relating to uncertainty in the instrument testing and calibration process. This is not an easy task, because a scan of literature in testing and metrology will reveal that all of the words related to testing, calibration, and uncertainty have been used more than once, and often in conflicting ways. The second area, to extend the current research is in overcoming barriers to the experimental evaluation of test uncertainty. It initially seems that simply running some of the classic CMM acceptance tests (ball bar, step gage, etc.) would reveal different errors when measured at different times, perhaps by different operators. The problem with this method is that the actual CMM performance and repeatability is always folded into the result, which can easily mask the actual effects of test uncertainty. It may be that the best (or only) method to perform this analysis of test uncertainty is through software simulation, where one contributor at a time can be varied.

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APPENDIX A: MATLAB CODE

Size tolerance program code

```
clc;
clear all
format long
numloops=100;                    % number of loops
numofpoints=30;                  % number of points on lines
sigma=.001;
[PTS1, PTS2]=generatept (numofpoints,sigma); %generate points on line
 for i=1:numloops                % for loop starts
[L1,P1]=generateline(PTS1,sigma);
PT1= projptline(L1,P1);
[L2,P2]=generateline(PTS2,sigma);
D1= ptlinedist(PT1,L2);
d(i,1) = D1(:,1);
 end
std_dev_distance= [std(d(:,1))]

% Function to generate Line
function [PtsOnline,avgpt]=generateline(data1,sigma)
 szdt1=length(data1);
 data2 = data1+sigma*randn(szdt1,2);   % Generate line with random numbers
 A=[ones(szdt1,1), data2(:,1)];
 ATA=A'*A;
 B=data2(:,2);
 ATB=A'*B;
 line=(inv(ATA))*ATB;                 % Generate line
 m1=length(data1);
 avgpt=(sum(data2))/m1;               % Average point
 PtsOnline=[line(2),-1,line(1)];      % generate point
function [pts1,pts2]=generatept(numofpoints,sigma)
length=100;
intpt=10;
for i=1:numofpoints
    genpt(i,1)=intpt;
    intpt=intpt+(length-20)/(numofpoints-1);
end
pts1=[genpt,zeros(30,1)];
pts2=[genpt];
pts2(:,2)=100;

%  Function Projected Point
function  projectedpt=projptline(L1,P1)
m1=L1(1);
```

```
a=m1;
b=L1(2);
c1=L1(3);
 if (a==0)
    c2=avgpt(1);
    projpt=[c2;c1];
 elseif (b==0)
    c1=-c1/m1;
    c2=avgpt(2);
    projpt=[c1;c2];
 else
    m2=-1/m1;
    c2=-m2*P1(1)+P1(2);
    M=[-m1,1;-m2,1];
    Intersecpt=[c1;c2];
    projpt=(inv(M))*(Intersecpt);
 end
 projectedpt=[projpt(1),projpt(2)];

% Line to point distance
function  distance=ptlinedist(PT1,L2)
 a=L2(1);
 b=L2(2);
 c=L2(3);
 x=PT1(1);
 y=PT1(2);
 q=sqrt((power(a,2))+(power(b,2)));
 distance=(abs(a*x+b*y+c))/q;
```

Position tolerance program

```
clear all
format long
numloops=2;
numofpoints=6;
sigma=.001;
ptsdatumA=[10,0;90,0];
ptsdatumB=[0,10;0,90];
for k=1:numloops
[CM1]=Generate_datum(ptsdatumA,sigma);
[CM2]=Generate_datum(ptsdatumB,sigma);
[Er]=Deviationpoints(CM1,CM2);
[XY]=Generate_circle_points(numofpoints,sigma);
[RT]= Translaterotate(CM1,XY,Er);
P1= circle_for_TUR(XY);
p(k,1)=P1(:,1);
end
```

```
std_dev_position=[std(p(:,1))]
% Generate Datums
function datum = Generate_datum(data1,sigma)
 szdt1=length(data1);
 data2 = data1+sigma*randn(szdt1,2);
 A=[ones(szdt1,1), data2(:,1)];
 ATA=A'*A;
 B=data2(:,2);
 ATB=A'*B;
% Generate circle points
function data2 = generate_circle_point(pnts,sigma)
angle=0;
for i=1:pnts
    theta(i,1)=angle;
    angle=angle+(360/pnts);
end
r=10;
szpt=length(theta);
Int_X=60+r*cosd(theta);
Int_Y=60+r*sind(theta);
data1=[Int_X,Int_Y];
data2=data1+sigma*randn(szpt,2);

% Deviation
function deviation=Deviationpoints(CM1,CM2)

c1=CM1(1);                  % Intersection point of datumB
m1=CM1(2);                  %slope of datumB
c2= CM2(1);                 %inresection point  of datumC
m2= CM2(2);                 %slope of datumC
E=[-m1,1;-m2,1];            %matrix with the slope
F=[c1;c2];                  %matrix with intersection points
deviation=(inv(E))*(F);     %find the X coordinate and Y coordinate of error
%Translate rotate the datums
function rot_trans=Translaterotate(CM1,XY,Er)
m1=CM1(2);
ang=atand(m1);                                   %angle of datum B
rot_theta=ang;                                   %make it theta
Position_Old=[XY(:,1),XY(:,2)];                  % make matrix with the old points
error=Er';                                       %transpose the position oferror
translation(:,1)=Position_Old(:,1)+error(:,1);   %making translation of x points
translation(:,2)=Position_Old(:,2)+error(:,2);   %making translation of y points
translation';                                    %transpose of translation
rotation=[cosd(rot_theta),sind(rot_theta);  -sind(rot_theta)  cosd(rot_theta)];  %Rotation matrix
```

```
rot_trans=[cosd(rot_theta),-sind(rot_theta);sind(rot_theta) cosd(rot_theta)]*translation';


% Generate Circle
function  positiontol=circle_for_TUR(XY)
 m=length(XY);
avgpt=(sum(XY))/m;
ptsX1=avgpt(:,1);
ptsY1=avgpt(:,2);
X1=XY(:,1);
Y1=XY(:,2);
flag1 =3;                                   %to excute while loop
 j=1;                                       %to execute condition for the shift of the result
  while  flag1>2
     if(j~=1)
         ptsX1=centerX1;                    %get the new value of pts of x coordinate
         ptsY1=centerY1;                    %get the new value of pts of y coordinate
      end
      j=j+1;
       for i=1:m
          sfptsX1(i,1)=X1(i,1)-ptsX1;         %shift the points of x coordinate
          sfptsY1(i,1)=Y1(i,1)-ptsY1;         %shift the points of y coordinate
       end
[theta1,r1]=cart2pol(sfptsX1,sfptsY1);          %change cartisian to polar
 ct=cos(theta1);                                %Column of cosine values
 st=sin(theta1);                              %column of sin values
ATA1=[sum((ct).*(ct)) sum((st).*(ct)) sum(ct);
     sum((st).*(ct)) sum((st).*(st)) sum(st);
      sum(ct) sum(st) m];                              %find the matrix A transpose A
ATB1=[sum(r1.*(ct));sum(r1.*(st));sum(r1)];        %find the matrix A transpose B
result1=(inv(ATA1))*ATB1;                           % find the result
X1not=result1(1,1);                                %x coordinate of the result
Y1not=result1(2,1);                                %y coordinate of the result
R1=result1(3,1);                                  %radius of the result

centerX1=X1not+ptsX1 ;
%shifting the x coordinate points of the center
centerY1=Y1not+ptsY1;                           %shifting the y coordinate points of the
center
  D1=2*R1;

if (abs(centerX1-ptsX1))<1e-12&& (abs(centerY1-ptsY1))<1e-12
   flag1=1;                                        %condition to terminate the  end
  end

   positiontol=2*(sqrt((power((centerX1-60),2))+(power((centerY1-60),2))));
```

APPENDIX B: UNCERTAINTY CALCULATION

Methods of evaluating the sources of uncertainty

The sources of uncertainty are evaluated through two methods:

Type A - Those evaluated by statistical methods.

Gage Repeatability & Reproducibility.

Type B - those evaluated by other means:

Manufactures specs, previous measurement data, general knowledge, calibration uncertainties, and “Engineering Judgments”.

Type A:

Repeatability

Surface finish, form

Operator skill

Type B:

Gage Block Uncertainty

Scale error of the micrometer

Zero point error of the micrometer

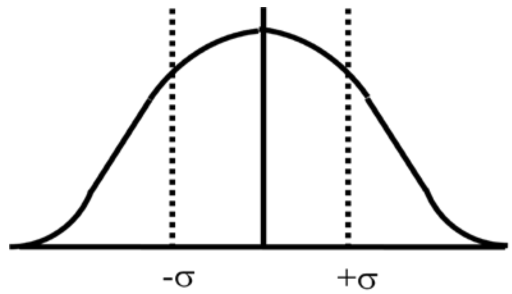
Parallelism of micrometer anvils

Delta temperature

Temperature of CTE (coefficient of thermal expansion)

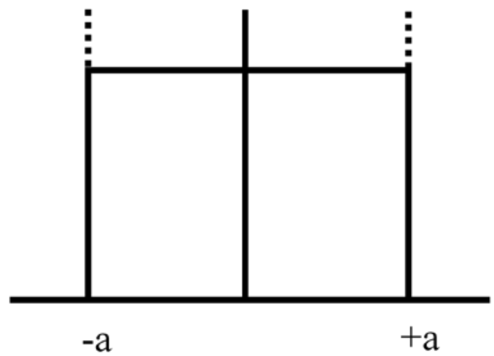
Standard Uncertainty Distribution Type

Normal Distribution



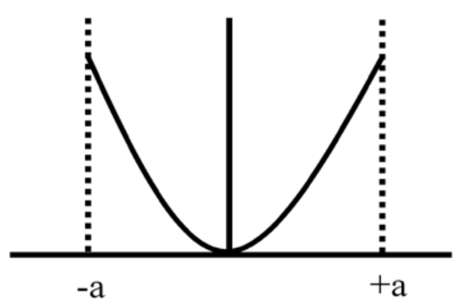
s = Standard Deviation (σ)

Rectangular Distribution



s = Equivalent Standard Deviation

$$s = \frac{a}{\sqrt{3}} = .58a$$



s = Equivalent Standard Deviation

$$s = \frac{a}{\sqrt{2}} = .71a$$

Sources	Type of distribution
Gage Block Uncertainty	Square
Repeatability	Normal
Scale error	Square
Zero point error	Square
Parallelism of micrometer anvils	Square
Delta temperature	U-Shape
Temperature of CTE	U-shape

Gage block uncertainty-

The gage block uncertainty was reported as 4 µin with a confidence level of 95% [1].

u_1 = 4 µin x .58 = 2.32 µin

Repeatability

A repeatability reading was performed on the micrometers by performing 20 repeated measurements in a controlled environment against a gage block. The resulting repeatability

u_2 = .29 µin [from data]

Scale error

Manufacturer's specifications state the maximum allowable error is +/- 2 µin

A square distribution is assumed where a = 2 µin

u_3 = 2 µm x .58 = 1.16 µin

Zero point error

Assuming manufacturer's specifications state the maximum allowable zero point error is +/- 2 µin. A square distribution is assumed where a = 2 µin

u_4 = 2 µin x .58 = 1.16 µin

Parallelism of micrometer anvil

Manufacturer's specifications state the maximum allowable parallelism error is 10µin

A square distribution of the influence of the parallelism error is assumed where a = 5 µin

u_5 = 5 µin x .58 =2.9 µin

Expansion due to temperature difference between gage block and micrometer

$\Delta L = \propto x \ \Delta T \ x L$

Assume, ΔT=0.5 ^oC, $\propto$=11.5ppm/ ^oC

ΔL=11.5ppm/ ^oC *0.5 ^oC*1in

= 5.75 µin

u_6 = 5.75 µin x .71 = 4.0825 µin

Uncertainty due to CTE

$\Delta L = \Delta \propto x \ \Delta T \ x L$

Assume, $\Delta \propto$ =15%$\propto$

=15%*11.5ppm/^oC

=1.725 ppm/^oC

Troom=73.8 ^oF = 23.2 ^oC

ΔL = 1.725 ppm/^oC*(23.2-20) ^oC*1in

= 5.52 µin

u_7 = 5.52 µin x .71 = 3.91 µin

Combined Uncertainty

$u_c = \sqrt{} \, u_1^2 + u_2^2 + u_3^2 + u_4^2 + \ldots\ldots\ldots$

$u_c = 6.96$

Standard Uncertainty, U=K u_c

Assume, coverage factor K=2,

$$U=2*6.96$$

$$=13.93$$

APPENDIX C: TEST UNCERTAINTY CALCULATION

Test Uncertainty Calculation from ISO/TS 23165

The recommended equation for the standard uncertainty of the error is

$$U\ (E) = \sqrt{u^2\ (\varepsilon_{cal}) + u^2\ (\varepsilon_{\alpha}) + u^2\ (\varepsilon_{t}) + u^2\ (\varepsilon_{align}) + u^2\ (\varepsilon_{fixt})}$$

Calculation for ISO 10360-2

Assuming,

$u\ (\varepsilon_{cal}) = 0.5\ \mu m$.

$u\ (\varepsilon_{\alpha}) = 1ppm/^{o}C \times .1\ ^{o}C\ x.3m = .03\ \mu m$

$u\ (\varepsilon_{t}) = .1 \times (10\text{-}8)\ ppm/^{o}C\ x1 = .2\ \mu m$

$u\ (\varepsilon_{align}) = 0$

$u\ (\varepsilon_{fixt}) = 0$

$U\ (E) = 0.539\ \mu m$

Calculation for ISO 10360-2

Assuming,

$u\ (\varepsilon_{cal}) = 0 \mu m$.

$u\ (\varepsilon_{\alpha}) = 1ppm/^{o}C \times .1\ ^{o}C\ x.3m = .03\ \mu m$

$u\ (\varepsilon_{t}) = .1 \times (10\text{-}8)\ ppm/^{o}C\ x1 = .2\ \mu m$

$u\ (\varepsilon_{align})$=May present, here assuming 0.

$u\ (\varepsilon_{fixt}) = 0$

$U\ (E) = 0.202\ \mu m$