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UNCERTAINTY BUDGET ESTIMATION IN WORN OUT ENGINE CYLINDER BORE MEASUREMENT PROCESS USING COORDINATE MEASURING MACHINE

[1]SANTOSH S. DABHOLE, [2]PROF. V. A. KULKARNI

[1] PG Student in Production Engineering (Manufacturing and Automation), D. Y. Patil College of Engineering, Akurdi, Pune, India
[2] Assistant Professor in Production Engineering, D. Y. Patil College of Engineering, Akurdi, Pune, India

santosh1152@rediffmail.com,kulkarnivinay@rediffmail.com

ABSTRACT: *All measurement data is subject to uncertainty and a measured value is only complete if it is accompanied by an appropriate statement of the associated uncertainty. The Guide to the Expression of Uncertainty in Measurement (GUM) published by International Organization for Standardization (ISO) is a key document used by National Measurement Institutes and industrial calibration laboratories as the basis of evaluating the uncertainty in the output of a measurement system Coordinate Measurement Machine (CMM) is used as precision metrological inspection equipment for wear monitoring of worn out surfaces because of its great capability of scanning freeform surfaces giving precise results. In this work an attempt is made to estimate the budget of uncertainties of the measurement results obtained by CMM which is used for dimensional inspection of worn out cylinder bore surface of air cooled petrol engine. The worn out regions are identified and the measurement uncertainty is estimated practically following rules in the Guide to the Expression of Uncertainty in Measurement (GUM).*

Keywords: **Coordinate Measurement Machine (CMM), Measurement uncertainty, Type A and Type B uncertainties, Precision measurement.**

1. INTRODUCTION

Today, reliable measurements are required over a much wider range of activities. In a measurement process even when all the measurement factors which can be controlled are controlled, repeated observation made during under the same condition, are rarely found identical. This is due to the variables like operator, reference standards, materials, instrument, environment, calibration, test methods etc. and therefore measurement results are never true value and in fact accompanied with uncertainty. Therefore the "measurement uncertainty" is a property of a measurement.

1.1 Project background

Coordinate Measurement Machine (CMM), finds its extensive application in surface scanning for newly machined form surfaces, worn out free form surfaces[1-2].Optimum economical allocation of resources to design, manufacture and metrology in a product is possible based on the knowledge of the magnitude of the uncertainties [3]. There are several stages in product life cycle where dimensional specifications or measurand behavior need to be continuously monitored aiming the increasing product lifecycle.

In the experimental study done by K.M. Pandey and others [4] it is found that low engine noise is obtained by reducing the clearance between piston and cylinder. Hence this is an important area of a research and development activity where uncertainty budget estimation in precision measurement process is used to build level of confidence for several pre-design, post-design activities like selection of heat treatment processes, coating applications as surface treatment, tolerance design, developing maintenance strategies etc.

1.2 Measurement Uncertainty: Economic aspects in decision making

Traditional Approach to assess the acceptance criteria for form tolerance or dimensional inspection is if measurand lie in upper tolerance limit and lower tolerance limit then decision conformation of acceptance is made.

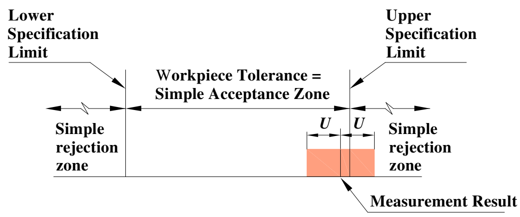


Fig.1.1: Measurement Result with uncertainty

Figure1.1 interprets that if measurand lie in proximity to Lower or Upper Specification Limits there is scope for doubt on measurand value or capability of metrological instrument because of uncertainties associated with measurand.

1.3 Problem Statement

Generally the CMM inspection results are not stated with the confidence level of measurement process. Salah Ali [1] has demonstrated the use of CMM in automotive domain for surface wear monitoring. He only considered Type-A uncertainty not used Type-B uncertainty but needs to be, because the measured results would have been used for decision making for tolerance design by design engineers, pre and post maintenance plan activities, manufacturing resource planning etc. and it is of great significance. Uncertainty if stated clearly and practically one can take logical and effective decisions.

In this project CMM is used in wear monitoring of single cylinder air cooled engine bore surface. The uncertainties associated with the measurand values are budgeted practically for a CMM measurement process and clear statement of confidence level is made while reporting the measurement results.

1.4 Project Objectives

The main objectives of this project are:

- Investigation of various types of sources of uncertainties in precision measurement process done by using CMM.
- To find out uncertainty budget estimation of measurement results for engine cylinder bore surface practically.
- Follow the rules in the Guide to the Expression of Uncertainty in Measurement (GUM) for the measurement process
- To find out worn surfaces locations of single cylinder air cooled engine cylinder bore surface

2. LITERATURE SURVEY

All real measurements have an almost infinite list of influence quantities that affect the measurement result.

2.1. Error Vs. Uncertainty

Error should not be confused with the term uncertainty. In metrology the error of a measurement is the difference between the result and the actual value of the measurand and uncertainty is the parameter, associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand. Error is an idealized concept and errors cannot be known exactly on the other hand uncertainty is a more practical concept.

2.2. Guide to the expression of uncertainty in measurement (GUM)

The Guide to the Expression of Uncertainty in Measurement (GUM) published by International Organization for Standardization (ISO) is a key document used by National Measurement Institutes and industrial calibration laboratories as the basis of evaluating the uncertainty in the output of a measurement system. As per ISO-GUM there are two categories of uncertainties viz. Type-A and Type-B.

2.3. Type-A Uncertainty

This is Standard uncertainty calculated statistically by repeated measurements under same conditions. When many measurements are made then generally the frequency plots of the measurements follow Gaussian or normal distribution. This uncertainty is nothing but standard deviation of measured set of readings.

2.4 Type-B Uncertainties

Uncertainties of measurement calculated by means other than statistical analysis are called Type-B Uncertainties. These uncertainties can be obtained from manufacturer's specifications, scientific judgment, calibration charts, experience etc. [22].

2.5 Sources of uncertainties in precision measurement systems

There is huge literature available for errors and uncertainties in precision measurement systems. However there is less work is done so far for the uncertainties in the measurement of geometric form deviations. Study of available literature show there are so many contributing factors to uncertainty of measurement results like wear of CMM structural members, noise of electrical devices, calibration uncertainties, operator skill, sampling methods, temperature variations, air pressure, humidity, probing system errors, software algorithm errors, repeatability error, factors like two dissimilar materials with different thermal coefficient of expansions, etc. [6-10]

A better estimation of uncertainty budget gives a strong base for appropriate and effective decision rules [11].Sphere temperature uncertainty, local error in CMM scale and the structure are other contributing sources in measurement uncertainty [12]

Trigger probes used in the surface form measurements shown variations in the mass and geometry of the stylus have their consequent effects on its inherent intrinsic dynamic characteristics that in turn would cause relevant systematic root errors in the resulting measurements [13].Also measurand is in influence with measurement plane, adaptor style, and stylus length, and stylus size, measurement speed of scanning [1] [14].

Pre-travel variation can be a dominant error source when using a CMM to inspect small features; [15].All simulation software has a finite list of uncertainty sources that can be included in the calculated uncertainty. Monte Carlo simulation method is used for many simulation software programs in error modeling. [16]

An approach to use of generalized confidence interval for a measurand is given by C.M. Wang and Hari K. Iyer [17] in the presence of Type-A and Type-B uncertainties under two different sets of assumptions on type –B errors.

3. METHODOLOGY

In order to meet the purpose of practical uncertainty budget estimation of the measurement, the study utilizes procedure laid down by GUM. It is simpler than the factorial design process [5] and easy adopt.

3.1. Uncertainty Budget Estimation Procedure

Following flowchart shows flow of the uncertainty budget evaluation process.

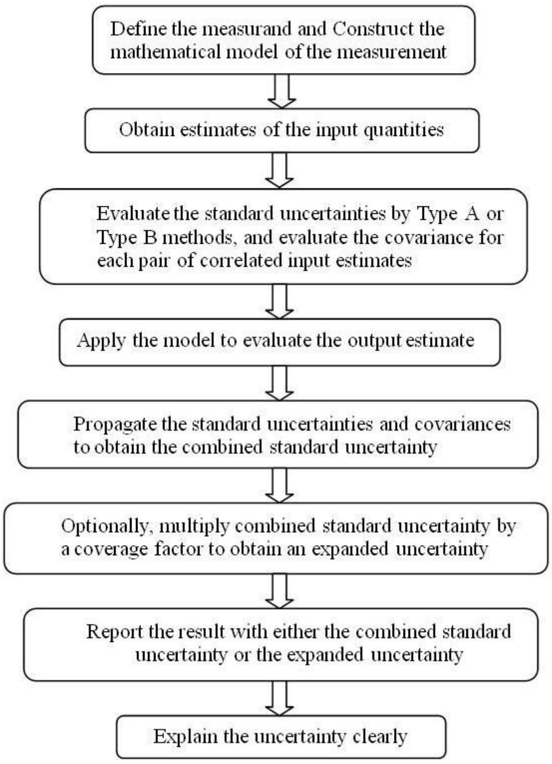


Fig.3.1: Uncertainty budget estimation procedure

3.2 Type-A uncertainty evaluation

Standard uncertainty is a standard deviation evaluated statistically. The PDF of the measurements follow Gaussian or normal distribution for the set of readings. If $x_1, x_2 \ldots . x_n$ are the n repeated measurements than the standard uncertainty(σ_{x1}) is given by

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad (1)$$

$$Var(x) = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \qquad (2)$$

Standard deviation of mean= $\frac{\sqrt{Var(x)}}{\sqrt{n}}$ (3)

Standard uncertainty$(\sigma_{x1}) = \frac{\sqrt{Var(x)}}{\sqrt{n}}$ (4)

Where$\bar{x}$ = mean, n = number of measurements.

3.3 Type-B uncertainty evaluation

The method of evaluation of uncertainty of measurement by means other than Type-A is the Type B evaluation. [5].The expected probability distribution function (PDF) is associated to all contributors and all the contributors needs to be normalized to standard uncertainty by some correction factor. The GUM in measurements provides correction factor of various distribution functions used in Type-B evaluation method. The correction factors of various distribution functions are shown in the Table 3.1.

Table 3.1: Correction Factors of Various Probability Density Functions

Sr. No	Distribution function	Divisor
1	Rectangular	$\sqrt{3}$
2	Triangular	$\sqrt{6}$
3	U shaped	$\sqrt{2}$
4	Normal	2– for 95% confidence level and 3– for 99% confidence interval

3.4 Combined Standard Uncertainty

After calculating the standard uncertainties for all the sources of uncertainty in your measurement then the total uncertainty in the measurement, called the combined standard uncertainty(σ_y).It is given by the root sum of square method (RSS method) of all the uncertainties in the measurement as

$$\sigma_y = \sqrt[2]{f_{x1}^2\sigma_{x1}^2 + f_{x2}^2\sigma_{x2}^2 + \cdots f_{xn}^2\sigma_{xn}^2} \qquad (5)$$

Where$f_{x1}, f_{x2} \ldots f_{xn}$ are the partial derivatives of the measurement model which represents the relationship between the input quantities and the measurand. The partial derivatives are called sensitivity coefficients, which give the effects of each input quantity on the final results (or the sensitivity of the output quantity to each input quantity).

$\sigma_{x1}, \sigma_{x2}, \ldots \sigma_{xn}$ represent the standard uncertainties obtained from Type A and Type B method.

3.5 Expanded Uncertainty

The term, expanded uncertainty is used in GUM to express the % confidence interval about the measurement result within which the true value of the measurand is believed to lie and is obtained by multiplying the combined uncertainty with coverage factor (k).The coverage factor (k) is obtained from Student's t distribution for corresponding effective degrees of freedom and confidence level.

Expanded uncertainty(U) is given by

$$U = k\sigma_y \qquad (6)$$

Where, k – coverage factor and σ_y is the combined standard uncertainty.

3.6 Degrees of Freedom (DOF):

For the Type-A evaluation of uncertainty, if the measurand x_i is observed independently for n times, the standard uncertaintyσ_{xi} can be obtained, and then its DOF can be calculated as,

$$v_{(xi)} = n - 1 \qquad (7)$$

For Type-B evaluation of uncertainty, the DOF of standard uncertainty σ_{xi} can be calculated as

$$v_{(xi)} \approx \frac{1}{2}\left[\frac{\Delta\sigma_{xi}}{\sigma_{xi}}\right]^{-2} \qquad (8)$$

Where $\left[\frac{\Delta\sigma_{xi}}{\sigma_{xi}}\right]$is relative standard uncertaintyof σ_{xi}, itsvalue can be obtained by experience.

The Welch-Satterthwaite formula is used to calculate the effective degrees of freedom for combined standard uncertainty σ_Y is given by

$$v_{eff}(Y) = \frac{(\sigma_Y)^4}{\sum_{i=1}^{n} \frac{(\sigma_{yi})^4}{v_i}} \qquad (9)$$

Where, v_i– Degrees of freedom for i^{th} uncertainty term

4. EXPERIMENTAL WORK

4.1 Mathematical model for measurement:

In the experiment an engine block come for overhaul is examined for its dimensional changes in bore surface because of wear in its service span. The inspection is done with precise CMM.

The mathematical model used in the uncertainty evaluation is

$$Y = x_i + \Delta x \pm U \qquad (10)$$

Where

Y = True value of measurand

x_i= dimension of measurand reported in actual inspection

Δx = errors in measurements and

U = expanded uncertainty

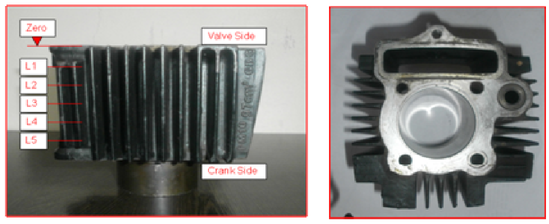
4.2 Inspection Methodology

4.2.1 Inspection part details:

Part name – Engine Cylinder block
Quantity - One
Type - Single cylinder air-cooled
Swept volume - 97.2 cc (cubic cm)
Stroke - 4-stroke
Combustion space- OHC (Over Head Combustion)
Nominal bore diameter- 50mm
Stroke length – 49.5mm

4.2.2 Inspection Sampling Plan:

First Zero is set at top surface of block as shown then at 10mm pitch downward and ten readings for diameter value and roundness values are taken transversally at levels L1, L2, L3, L4 and L5 successively. For the concentricity, axial centre of bore diameter at level L1 is set as a reference datum and with respect to it concentricity for the bore diameters at levels L2, L3, L4, and L5 is measured see, fig. 4.1(a).



(a): Different levels (b) Top View of Block

Fig.4.1: Sampling Plan

4.3 Experimental Set-up

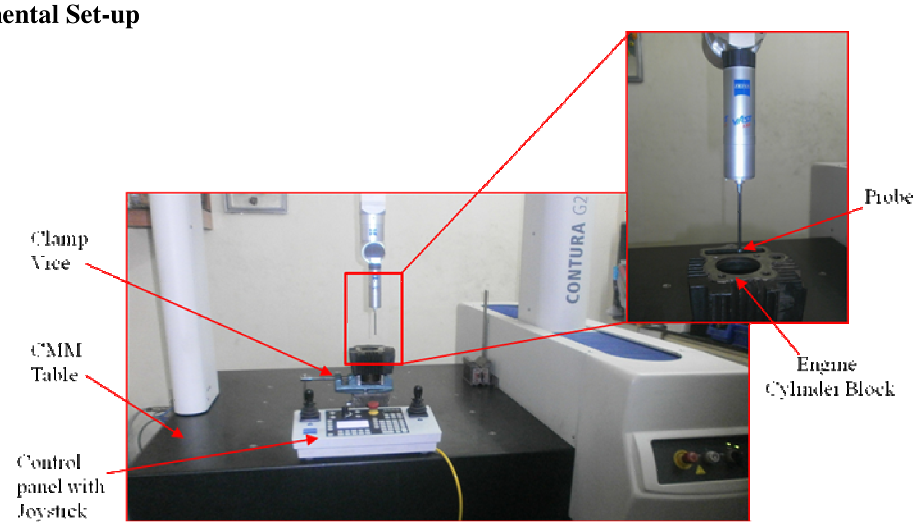


Fig.4.2: Experimental Set-up of CMM

4.3.1 Inspection Machine Specifications:

Table 4.1: Specification of CMM

Sr. No.	Particular	Description
Make : Carl Zeiss		
Model : CONTURA G2 RDS VAST XXT		
1	Size	700x700x600 mm
2	Volumetric Accuracy	(1.8+L/300) µm
3	Resolution	1.8 µm
4	Repeatability MPE_E*	1.8 µm
*MPE_E: Maximum Permissible length measuring Error based on ISO 10360-2		

4.3.2 Other details

1) Scanning speed of probe: 10mm/sec
2) Stylus used: Silicon Nitride Stylus M3 XXT,
3) Uncertainty in Calibration Gauge Block of 50 mm : 1.1 µm
4) Room Initial temperature (T_1): 20 °C
5) Room Temperature at end(T_2): 21°C
6) Reference Temperature(T_{ref}): 20 °C
7) Humidity: 60 ±5 %
8) Thermal coefficient of Silicon Nitride Sphere(α_P): 2.9×10^{-6} mm/m /°C
9) The soaking time for engine block = 8 hour

5. INSPECTION RESULTS AND CALCULATIONS

5.1Mean and Standard Uncertainty for ten inspection readings and respective Type-A Uncertainty:
Following table are giving results of ten readings and standard uncertainty of measured results.

5.1.1 For Bore diameter measurement:

Table 5.1: Mean and standard uncertainty for ten readings

Particular	Bore diameter, mm				
	Level				
	L1	L2	L3	L4	L5
Mean (mm)	50.047	50.025	50.027	50.031	50.030
Standard Uncertainty (µm)	0	0.425	0	0	1.897
Maximum Standard Uncertainty inRepeatability for Bore diameter σ_{x1_D},(µm)					**1.897**

5.1.2 For Roundness Measurement:

Table 5.2: Mean and standard uncertainty for ten readings

Particular	Roundness (R_a), µm				
	Level				
	L1	L2	L3	L4	L5
Mean (µm)	15	8.8	11.4	17.4	16.6
Standard Uncertainty (µm)	0	0.632	0.516	0.516	2.716
Maximum Standard Uncertainty inRepeatability for Roundness σ_{x1_R}, (µm)					**2.716**

5.1.3 For Concentricity:

Table 5.3: Mean and standard uncertainty for ten readings

Particular	Concentricity, µm				
	Level				
	L1	L2	L3	L4	L5
Mean (µm)	0	6.3	5.1	4.1	3.9
Standard Uncertainty (µm)	0	1.494	0.994	0.316	0.316
Maximum Standard Uncertainty inRepeatability for Concentricity σ_{x1_C},(µm)					**1.494**

5.2 Calculations for Type-B Uncertainty Budget Estimation

1. Standard uncertainty due to change in lab Temperature(σ_{x2}) and assuming rectangular distribution ,
   $\sigma_{x2} = \Delta T/\sqrt{3}$
   $= 1/\sqrt{3}$
   = 0.5774µm
   Where $\Delta T = T_1 - T_2$
2. Standard uncertainty due to Thermal expansion of probe material (σ_{x3}):
   By considering only 10% of α_P
   Estimated uncertainty = 0.1 x 0.0029
   = 0.00029µm
   Assuming 'U' distribution,
   $\sigma_{x3} = 0.00029/\sqrt{2}$
   = 0.00021µm
3. Standard uncertainty due to Resolution of Equipment (σ_{x4}):
   Estimated uncertainty = 1.8 µm
   Assuming Rectangular distribution,
   $\sigma_{x4} = 1.8/\sqrt{3}$
   = 1.0392µm
4. Standard uncertainty due to Form error in Reference Sphere (σ_{x5}):
   Estimated uncertainty = 0.071 µm
   Assuming Rectangular distribution,
   $\sigma_{x5} = 0.071/\sqrt{3}$
   = 0.0409 µm
5. Standard uncertainty due to calibration of Gauge block (σ_{x6}):
   Estimated uncertainty = 1.1 µm (from Calibration certificate),
   Assuming Rectangular distributions,
   $\sigma_{x6} = 1.1/\sqrt{3}$
   = 0.6350 µm

6. RESULTS AND DISCUSSIONS

6.1 Summary of Results

Following tables spreadsheet for Type-A and Type –B uncertainty budget evaluations.

6.1.1 Expanded Uncertainty for Bore Diameter Measurement

Table 6.1: Expanded Uncertainty Spread-sheet – Bore Diameter

Source of Uncertainty	Estimate (µm)	PDF, Type and Divisor Factor		Standard Uncertainty	Sensitivity Coefficient	Degrees of Freedom	Uncertainty (µm)
		Type	Factor				
Repeatability for Roundness (σ_{1_D})	1.89	Type-A, Normal	2	0.945	1	9	0.945
Change in lab Temperature (σ_{x2})	1.0	Type-B, Rectangular	$\sqrt{3}$	0.5774	1	∞	0.5774
Thermal expansion of probe material (σ_{x3})	0.00029	Type-B, 'U'	$\sqrt{2}$	0.00021	1	∞	0.00021
Resolution (σ_{x4})	1.8	Type-B, Rectangular	$\sqrt{3}$	1.03923	1	∞	1.03923
Form error in Reference Sphere (σ_{x5})	0.071	Type-B, Rectangular	$\sqrt{3}$	0.0409	1	∞	0.0409
Calibration of Gauge block (σ_{x6})	1.1	Type-B, Rectangular	$\sqrt{3}$	0.6350	1	∞	0.6350
Combined Uncertainty ,$\sigma_{Y_D} = \sqrt[2]{f_{x1}^2\sigma_{x1_D}^2 + f_{x2}^2\sigma_{x2}^2 + \cdots f_{x6}^2\sigma_{x6}^2}$							1.6466
`Coverage Factor, **k = 2**							
Expanded Uncertainty, **U = k**σ_{Y_D}							± 3.2932

6.1.2 Expanded Uncertainty for Roundness Measurement

Table 6.2: Expanded Uncertainty Spread-sheet - Roundness

Source of Uncertainty	Estimate (µm)	PDF, Type and Correction Factor		Standard Uncertainty	Sensitivity Coefficient	Degrees of Freedom	Uncertainty (µm)
		Type	Factor				
Repeatability for Roundness (σ_{1_R})	1.8 (2.71621)	Type-A, Normal	2	1.3581	1	9	1.3581
Change in lab Temperature (σ_{x2})	1.0	Type-B, Rectangular	$\sqrt{3}$	0.5774	1	∞	0.5774
Thermal expansion of probe material (σ_{x3})	0.00029	Type-B, 'U'	$\sqrt{2}$	0.00021	1	∞	0.00021
Resolution (σ_{x4})	1.8	Type-B, Rectangular	$\sqrt{3}$	1.03923	1	∞	1.03923
Form error in Reference Sphere (σ_{x5})	0.071	Type-B, Rectangular	$\sqrt{3}$	0.0409	1	∞	0.0409
Calibration of Gauge block (σ_{x6})	1.1	Type-B, Rectangular	$\sqrt{3}$	0.6350	1	∞	0.6350
Combined Uncertainty , $\sigma_{Y_R} = \sqrt[2]{f_{x1}^2\sigma_{x1_R}^2 + f_{x2}^2\sigma_{x2}^2 + \cdots f_{x6}^2\sigma_{x6}^2}$							1.9138
Coverage Factor, **k = 2**							

Expanded Uncertainty, **U = k** σ_{Y_R}	±3.8276

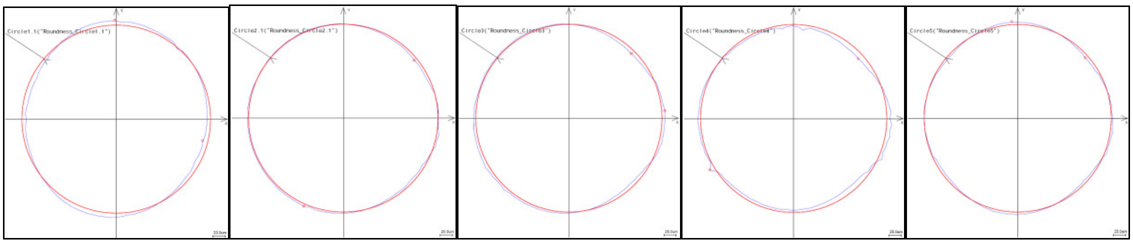
6.1.3 Expanded Uncertainty for Concentricity Measurement

Table 5.3: Expanded Uncertainty Spread-sheet - Concentricity

Source of Uncertainty	Estimate (µm)	PDF, Type and Correction Factor		Standard Uncertainty	Sensitivity Coefficient	Degrees of Freedom	Uncertainty (µm)
		Type	Factor				
Repeatability for Concentricity (σ_{1_C})	1.8 (1.49443)	Type-A, Normal	2	0.9	1	9	0.74722
Change in lab Temperature (σ_{x2})	1.0	Type-B, Rectangular	$\sqrt{3}$	0.5774	1	∞	0.5774
Thermal expansion of probe material (σ_{x3})	0.00029	Type-B, 'U'	$\sqrt{2}$	0.00021	1	∞	0.00021
Resolution (σ_{x4})	1.8	Type-B, Rectangular	$\sqrt{3}$	1.03923	1	∞	1.03923
Form error in Reference Sphere (σ_{x5})	0.071	Type-B, Rectangular	$\sqrt{3}$	0.0409	1	∞	0.0409
Calibration of Gauge block (σ_{x6})	1.1	Type-B, Rectangular	$\sqrt{3}$	0.6350	1	∞	0.6350
Combined Uncertainty , $\sigma_{Y_C} = \sqrt[2]{f_{x1}^2\sigma_{x1_C}^2 + f_{x2}^2\sigma_{x2}^2 + \cdots f_{x6}^2\sigma_{x6}^2}$							1.5416
Coverage Factor, **k = 2**							
Expanded Uncertainty, **U = k** σ_{Y_C}							±3.0832

6.2CAD plots of measurement results

Following are the sample CAD Plots obtained by a CALYPSO Software of CMM for first measurement of roundness reading at each level.



(a)at L1 **(b) at L2** **(c) at L3** **(d) at L4** **(e) at L5**

Fig. 5.1: First Reading Roundness CAD plots at each level

Observing CAD plots it seen that wear of a bore is in elliptical profile is happened. This is due to unbalanced dynamic forces in piston sliding mechanism. This is due to unbalanced dynamic forces and uneven lubrication in piston sliding mechanism. The red dots in CAD plots are peak crest and trough points in the roundness profile.

6.3 Discussion: Measurement Result Statement

Following the ISO-GUM for CMM, in inspection report all the Type-A and Type-B uncertainties must be clearly specified as,

1) For Bore Diameter, all measured readings are having maximum Expanded uncertainty *(U)*= ±3.2932µm
2) For Roundness, all measured readings are having maximum expanded uncertainty *(U)*= ±3.8276µm
3) For Concentricity, all measured readings are having maximum expanded uncertainty *(U)*= ±3.0832µm, with coverage factor (k) = 2, ∞ degrees of freedom, at confidence level of 95%.

7. CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

Analyzing the CMM measurements' uncertainty results of this experimental study following conclusions can be made

- It is seen that when measuring the dimensions of small, the uncertainty value has a significant impact on the measurement results. Therefore measurement uncertainty must be stated clearly on the inspection results.

- Inspection Laboratories must calculate the uncertainty budget as a part of measurement evaluation to provide high quality measurement results.
- Careful calibration of measuring instruments and equipment by measurement standard is of the utmost importance, calibration uncertainty is also a contributor in expanded uncertainty budget estimation.
- When designer specifies "tight" tolerance for the object he must specify the allowable expanded uncertainty for which parts is accepted.
- If CMMs are used for worn out surface wear monitoring, measurement uncertainty must be stated with results. This will help to decide strategy for maintenance, designer to design tolerance specifications.

7.2 Future Scope

- Standardization needs to be defined for reduction in geometrical dimension uncertainty measurements.
- Scope for Optimization for the process plan can be found out.

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