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A Review Paper Optimising Metrology of Involute Contour by Coordinate Measuring Machine

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Abstract:

This paper proposes a simple and effective method for the metrology and inspection of Involute contour of a work. Based on the coordinates and normal vector of each specified point on the Involute profile, the data required to move the CMM inspection probe to the surface of the tooth are then obtained. A least-square fitting method is planned to minimize the inspection error caused by a misalignment of actual with respect to reference datum. Metrology in recent years witnessed growing requirement of less measurement lead time, reduced setups, flexibility and less human intervention in measurement process. Coordinate Measuring Machines and systems are developed to fulfil these needs of accelerated measurement cycles with accurate measurements. This review work focus on design and development of improvised method for interim check by CMM by operator enabling geometrical error pooling mechanism for CMM mapping along with identification of best Job position on CMM table and compensation thereafter.

Index Terms – Coordinates, Errors, Measurements, Metrology, Mapping

I. INTRODUCTION

Advent of automation gave rise to formation of flexibility and 3D measurement strategies with very less measurement lead time (MLT). Advance Coordinate Metrology provides distinct advantages over conventional Metrology as manual Alignment is no longer a necessity, Changing measurement tasks can be adapted by using software, one reference system can be used for size, form, location and orientation computation in least number of steps, measurement performance can be mathematically or numerically modelled and also used for comparison between various measurement standards, manual nature of throughput can be replaced with automatic cycles.

II. Coordinate Measuring Machine (CMM) As Basis of Advance Coordinate Metrology

Coordinate Measuring Machines (CMMs) are extremely powerful metrological instruments: they enable us to locate point coordinates on three-dimensional structures at the same time that they integrate both dimensions and

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the orthogonal relationships. When we add a computer to the CMM, we create an instrument that can automatically perform complex analysis and that can learn measurement routines to compare how a piece conforms to its specifications. Instead of performing time consuming measurement with traditional, single axis instruments (micrometers, height gages, etc.) and cumbersome mathematics, you can dimensionally evaluate complex work pieces with precision and speed and you can store the data for later analysis or comparisons. The greater the complexity of the piece, the greater the benefits from a CMM.

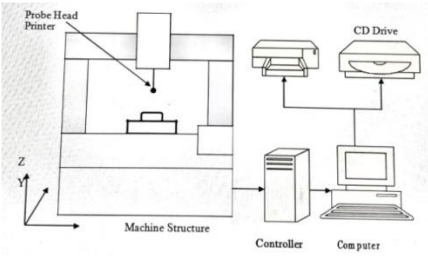

Fig 1.1 Components of CMM system

Figure 1.1 shows the assembly of components of CMM system.[2][4] In CMM systems, Measurement by coordinate geometry requires a method to measure individual points in space. Machine using 3-Dimensional rectilinear Cartesian coordinate system for physical realization with moving axes is best used for generating measurement data sets. These data sets can further be utilized to compute dimensional quantities, position of features, such as flatness, circularity, cylindricity, perpendicularity, concentricity etc

2.1PROBING SYSTEM

It is the part of an Inductive and optical transmission probes have been developed for automatic tool changing. Power is transmitted using inductive linking between modules fitted to the machine structure and attached to the probe. The hard-wired transmission probe shown is primarily for tool setting and is mounted in a fixed position on the machine structure .CMM that sense the different parameters required for the calculation. Appropriate probes have to be selected and placed in the spindle of the CMM. The transmission probe allows probe rotation between gauging moves, making it particularly useful for datuming the probe. The wide-angle system allows greater axial movement of the probe and is suitable for the majority of installation

III. CMM CALIBRATION

Joint Committee for Guides in Metrology (JCGM 200:2008) defines Calibration as specified condition of operations in two steps

To establish relation between measurement indications and quantity values provided by measurement standards, both associated with measurement uncertainties.

Use of first step to setup measurement result by indication. Calibration is also expressed by function, diagram, tables, curves, statements [3]. JCGM 200:2008 also associates measurement error and calibration as

1) The measurement error concept is used for a single reference quantity value, resulting from calibrated equipment having negligible measurement uncertainty. Also, known measurement error in specified conventional quantity value.[6]

2) Calibration process demonstrates validity of measurement results dependency on metrological properties.[6]

Therefore it can be taken that measurement error is function of calibration and the metrological properties of instruments used in calibration and it is associated with Measurement Uncertainty. Verification of CMM performance is normally carried out in two time required time intervals with two complexity levels. The primary calibration cycle is normally referred as one year and secondary cycle period should be identified based on interim checks or verification results.

3.1 Measurement Uncertainty

Rigid body errors, sampling strategies, fitting algorithms, probing errors, machine dynamic errors including environmental changes and similar parameters affect CMM accuracy. Specifying measurement uncertainty for various measurement tasks is restricted due to wide applications of CMM. National and International Standards specifies the ways and means of CMM measurement uncertainty estimation. These standards prescribe special tests on simple artifacts to make fair comparison between different CMMs.

3.2 Use of Artifact over Laser Interferometer

Conventionally the evaluations of large CMMs (An axis >2 meters) are conducted by using Laser Interferometers in which CMM probe is replaced by retro reflector in ram. It holds good for majority of CMMs. However, for few CMMs, equipped with error maps, it is inappropriate as CMM measurements correct point coordinates after probe triggering event. The retro reflector held in CMM ram will not report the corrected coordinates due to absence of triggering event.

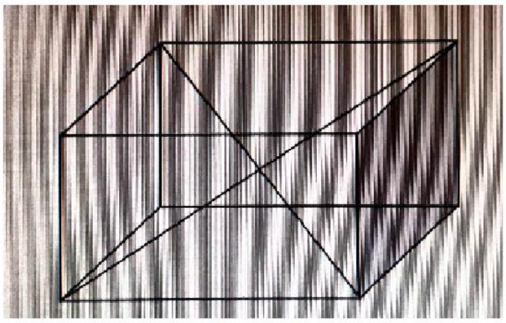

Fig. 1.2 **Measuring Volume**

In this case, the laser interferometer reported positional accuracy instead of measuring accuracy. The purpose of research will be to develop

1) Produce Ball plate utilizing desirable characteristics as per fig 1.3 for CMM interim check.[12]

2) Geometrical errors pooling mechanism

3) Mechanism to identify “Best job position on CMM”

4) Operator enabled interim checks for CMM

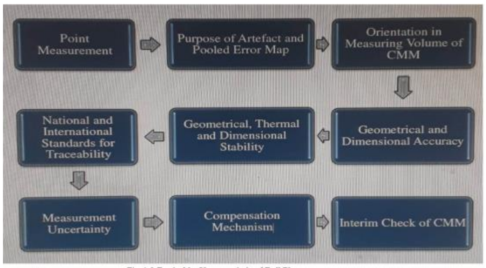

Fig. 1.3 **Desirable Characteristic of Ball Plate**

3.3 Errors in Measurement Process by CMM

CMM is used for determination of physical geometrical characteristics of the workpiece. The geometrical characteristics of an object can be in varied form that includes Dimensions – 2D Distances, 3D Distances and Angle Form – Straightness, roundness, cylindricity, sphericity and flatness Orientation – Parallelism, Perpendicularity, Concentricity, Angularity and Coaxility.

- Features – Point, 2D and 3D Line, Circle, Sphere, Cone, Cylinder, Plane, Location, Slot, Bore, Offset, Hole
- Profile – Surface, Scanning

3.4 Theoretical framework for CMM measurement uncertainty

CMM uncertainty evaluations or mathematical modelling critically requires CMM maintenance under stated and implied conditions as per national and international standards.[16]

3.4.1 Scale Errors

A scale is attached with CMM for each movement of axis. This scale is configured with either mechanical or optical/laser configuration. The attempt will be made to compensate positional errors occurring due to scale errors through hardware or software, due to inherent inaccuracies of CMM structure.

3.4.2Workpiece Errors

Workpiece errors occur due to form deviation errors of workpiece or measurand. These errors are resulted due to repeatable aspects of CMM performance such as rigidity and workpiece fixturing. Measurement errors are affected due to temperature variation of work piece and CMM and deviation of resultant values with true value.

3.4.3 Probe System Errors

Probe system is the most influencing factor for accuracy. It consists of various components as shown in following table with their characteristics

3.4.4 Feature Form Errors

All physical materials are equipped with individual features with or without deviation from perfect geometries like plane or flatness, line or straightness, circle or roundness cylinder or cylindricity. Especially datum features with deviations affect the performance of CMM with respect to uncertainty.

3.4.5 Fitting algorithm errors

CMM uses software for processing collected data points by probe system. Curve and surface fitting by these data points affects CMM performance extensively. Fitting algorithms are assed for form deviation, location and features. Various methods are available for establishing fitting algorithms like least squares fit (LSF) (Gaussian fit), Minimum zone fit (MZF), Maximum Inscribed and Circumscribed (MIF and MCF) fits for standard shapes like planes, spheres, cylinders, lines, cones and torus. For 2D fits, all picked up data points lie and generate resultant fitting in same plane. However for 3D fits data in different planes are considered for fitting algorithms. All fitting algorithms aim for minimum residues for fitment.

3.4.6 Probing Errors

Probing error contribute to measurement uncertainty for each task by CMM. As per ISO 10360-5, probing error is major contributor in maximum permissible error (MPE). It recommends computing probing errors by measurement of 25 points distributed evenly to estimate radial distance of most interior to most exterior measured point. The probing error is directly proportion to measurement speeds and is a function of type, quality of probing system, probe qualification procedure and size and spatial variations.

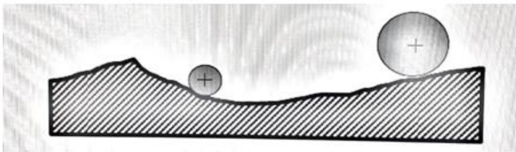

Fig. 1.4 **Ball tip contour fitness to workpiece form**

3.4.7Geometric Errors (X, Y, Z Axis)

CMM based on workpiece and probe movements separated by letter F as depicted in table 1.1. [4]

Table 1.1 **CMM Workpiece and probe movements notations**

Sr. No	Notation	Motion	
		Probe	Workpiece (CMM table)
1.	FXYZ	XY, YZ and ZX plane	-
2.	XFYZ	YZ plane	X direction
3.	YXFZ	Z direction	YX plane
4.	ZYXF	-	ZY, YX and ZX plane
5.	XYFZ	Z direction	XY Plane

Three translational Cartesian CMM axes have six degrees of freedom with possible six errors each, counting 18 geometric errors and 3 squareness errors amongst the axes. ISO 230-2 defines these 21 geometric errors affecting performance of CMM. For CMM having possible movements in all three axes, 21 geometrical errors as per ISO 230-2 can be represented as shown in table 1.2[4]

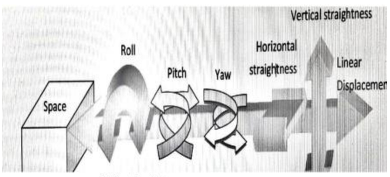

Fig.1.5 Geometric Error Schematic

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For CMM having possible movements in all three axes, 21 geometrical errors as per ISO 230-2 can be represented as shown in table 1.2[4]

Table1.2 Geometric Error Notations

Sr. No	Description	X	Y	Z
1.	Linear Displacement Errors	$\delta_x(x)$	$\delta_y(y)$	$\delta_z(z)$
2.	Vertical Straightness Errors	$\delta_y(x)$	$\delta_x(y)$	$\delta_x(z)$
3.	Horizontal Straightness Errors	$\delta_z(x)$	$\delta_z(y)$	$\delta_y(z)$
4.	Roll Angular Errors	$\varepsilon_x(x)$	$\varepsilon_y(y)$	$\varepsilon_z(z)$
5.	Pitch Angular Errors	$\varepsilon_y(x)$	$\varepsilon_z(y)$	$\varepsilon_x(z)$
6.	Yaw Angular Errors	$\varepsilon_z(x)$	$\varepsilon_x(y)$	$\varepsilon_y(z)$
7.	Squareness Errors	S_{xy}	S_{yz}	S_{zx}
Roll – Self Rotation around axis ↻	Pitch – Vertical up and down ↕	Yaw – Horizontal Right and Left ⟷		

4.0 Mathematical Model for Compensation

Following are the recommended steps for mathematical model used for compensation mechanism established in CMM

- Mechanism to compute measurements errors within measurement volume in various working conditions
- Relationship of machine functional errors and parametric errors such as geometric, thermal errors
- Model should abstract CMM machine measurement mechanism and reflect real behaviour of machine itself
- Approximations made must be within certain limits and easy to practice

4.1 Mathematical Modelling of Errors

Zhang et al[14] modelled angular error motions in form of matrix as per following.

$$R(X)=\begin{pmatrix}\cos(\varepsilon_z(X)) & \sin(\varepsilon_z(X)) & 0\\ -\sin(\varepsilon_z(X)) & \cos(\varepsilon_z(X)) & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\cos(\varepsilon_y(X)) & 0 & -\sin(\varepsilon_y(X))\\ 0 & 1 & 0\\ \sin(\varepsilon_y(X)) & 0 & \cos(\varepsilon_y(X))\end{pmatrix}$$

$$\begin{pmatrix}1 & 0 & 0\\ 0 & \cos(\varepsilon_x(X)) & \sin(\varepsilon_x(X))\\ 0 & -\sin(\varepsilon_x(X)) & \cos(\varepsilon_x(X))\end{pmatrix}$$

Where R(x) is rotational matrix of x motion.

Considering smaller magnitude of angular errors corresponding values are replaced by sine values and "1" by cosine errors.

$$R(X)=\begin{pmatrix}1 & \varepsilon_z(X) & 0\\ -\varepsilon_z(X) & 1 & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & -\varepsilon_y(X)\\ 0 & 1 & 0\\ \varepsilon_y(X) & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & \varepsilon_x(X)\\ 0 & -\varepsilon_x(X) & 1\end{pmatrix}$$

$$R(X)=\begin{pmatrix}1 & \varepsilon_z(X) & -\varepsilon_y(X)\\ -\varepsilon_z(X) & 1 & \varepsilon_x(X)\\ \varepsilon_y(X) & -\varepsilon_x(X) & 1\end{pmatrix}$$

Similarly

$$R(Y)=\begin{pmatrix}1 & \varepsilon_z(Y) & -\varepsilon_y(Y)\\ -\varepsilon_z(Y) & 1 & \varepsilon_x(Y)\\ \varepsilon_y(Y) & -\varepsilon_x(Y) & 1\end{pmatrix}$$

$$R(Z)=\begin{pmatrix}1 & \varepsilon_z(Z) & -\varepsilon_y(Z)\\ -\varepsilon_z(Z) & 1 & \varepsilon_x(Z)\\ \varepsilon_y(Z) & -\varepsilon_x(Z) & 1\end{pmatrix}$$

$$\Delta X = \delta_x(X)+\delta_x(Y)+\delta_x(Z)-YS_{xy}-ZS_{zx}-Y\varepsilon_x(X)+Z[\varepsilon_y(X)+\varepsilon_y$$
$$Y_{P3}[\varepsilon_Z(X)+\varepsilon_Z(Y)+\varepsilon_Z(Z)]+Z_{P3}[\varepsilon_Y(X)+\varepsilon_Y(Y)+\varepsilon_Y(Z)]$$

$$\Delta Y = \delta_Y(X)+\delta_Y(Y)+\delta_Y(Z)-ZS_{yz}-Z[\varepsilon_x(X)+\varepsilon_x(Y)]+X_{P3}[\varepsilon_Z(X)$$
$$\varepsilon_Z(Z)]-Z_{P3}[\varepsilon_x(X)+\varepsilon_x(Y)+\varepsilon_x(Z)]$$

$$\Delta Z = \delta_z(X)+\delta_z(Y)+\delta_z(Z)+Y\varepsilon_x(X)-X_{P3}[\varepsilon_y(X)+\varepsilon_y(Y)+\varepsilon_y(Z)]$$
$$Y_{P3}[\varepsilon_x(X)+\varepsilon_x(Y)+\varepsilon_x(Z)]$$

Error motions of probe tip are given by various equations
where ΔX, ΔY, ΔZ are error motions in X, Y and Z directions respectively.

$$R(Z)=\begin{pmatrix}1 & \varepsilon_z(Z) & -\varepsilon_y(Z)\\ -\varepsilon_z(Z) & 1 & \varepsilon_x(Z)\\ \varepsilon_y(Z) & -\varepsilon_x(Z) & 1\end{pmatrix}$$

- Graphical Summary

The Graphical Summary for First Month and Second Month comprising of histogram with an overlaid normal curve, box plot, 95% confidence intervals of population and median Pearson Correlation Coefficient. The relationship between the analyzed series X and Y, correlation coefficient is expressed. Selective co-variance is calculated.

Correlations: D (1-6), D (1-12)

Pearson correlation of D (1-6) and D (1-12) = 0.973, which indicates, difference of values of 1st to 6th Month and 1st to 12th Month shows strong positive relationship. However, the recalibration period of Ball Plate needs to be established.

- Cross Correlation

For analyzing, for what period the artifact retains the ball dimensions before it is required to be recalibrated, a correlation graph is required to be plot.

The cross correlation graph indicates, cross correlation of lag -6 and +6 is below significance of 5% (0.05). This indicates that ball plate retains dimensions well, till 11th month and it can be used without any calibration or dimensions check till 11month at stretch.

- Auto-Correlation

Autocorrelation refers to the correlation of a time series with its own past and future values. Autocorrelation also defined as lagged correlation between data arranged in time. It plots and computes correlations of a time series separated by k time units. This is known as Autocorrelation Function (ACF).

- Autocorrelation Function

To measure correlation between observations at different times, series of quantities called sample autocorrelation is used to check persistence in time series. Autocorrelation Function (ACF) is a set of autocorrelation coefficients arranged as a function of separation of time called as Lag. The autocorrelation coefficient and product moment coefficients are closely related.

Anderson-Darling Normality Test

Anderson-Darling Normality Test measures the area between the chosen line of fitted distribution and the nonparametric step function. The statistics is a squared distribution weighted more for tails of the distribution. Smaller Anderson-Darling Values fits data to the chosen distribution.

H_0 = Data Follow Normal Distribution, H_A = Data not following Normal Distribution

IV. RESULTS AND DISCUSSION

4.1 Conclusion

Metrology in recent years has witnessed growing requirements in terms of reduction in measurement lead time and human intervention coupled with increased accuracy and reliability. CMM (Coordinate Measuring Machine) fulfils this requirement. CMM is a device which enables dimensional and form measurements to users, even for complicated 3D objects. Numerous techniques for monitoring the long term stability and accuracy of CMM are required to be studied and modified according to growing dynamic needs of user. One of them involves used of artifacts. These artifacts are not only used for CMM evaluation but also for interim checks of CMM. There are numerous types and configurations of artifact used in industry. As artifacts of suitable design can reveal probing errors in addition to axis movement errors that are normally calibrated using laser interferometers, artifacts usage is most preferred.

V. ACKNOWLEDGMENT

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