Statistical Performance Analysis of Zirconia-Dolerite Ball Plate for Dimensional Stability

VA Kulkarni, B.B. Ahuja

Abstract— ***A novel artifact zirconia-dolerite ball plate is developed for interim check of coordinate measuring machine. Artifact contains 52 balls and distances between balls are used for analysis of measuring volume of CMM. Statistical performance analysis is explained in this paper. Stability of Ball plate is explored through cross correlation. The resultant corroleogram depicts that the ball plate can be used for 11 months without recalibration or rechecking for dimensional stability.***

Index Terms—***Artifact, Ball Plate, Run Test, Cross Correlation***

I. INTRODUCTION

ISO 10360 -1:2000 (IS 15635 Part-I: 2006) defines CMM (Coordinate Measuring Machine) as a measuring system with means to move a probing system and capability to determine spatial coordinates on workpiece surface. CMM enables easy measurement of even complicated three-dimensional components, collecting measurements of geometrical points. These advantages result in the great popularity of the CMM machine as the main instrument for parts inspection [1]. Several techniques for parametric calibration of CMMs have been developed in the past either using Artifacts like ball plates, ball bars, etc or laser interferometers and electronic levels [2]. Error Measurements for a coordinate measuring machine (CMM) described in ISO 10360 series contain test with a different concept. By using an Artifact such as ball plate, all the three-dimensional position error components (in X,Y and Z) for the given reference location are directly measured over the entire workspace[3]. In order to improve the calibration result, a simple artifact is used in several different locations and orientations, referred as multiple simple artifact. The calibration result with the multiple simple artifact is equivalent to that with 3D artifact in simulation and experiment. As the CMM is a measuring machine to measure a discrete point in 3D space, a point is most adequate artifact to the CMM. So the spheres are adopted as the artifact and the center of spheres are reference points [4].

However, performance of Ball plate is affected by several parameters listed in Table I.

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Table I: Ball Plate Desirable Characteristics

Sr. No.	Ball Plate Characteristics	Factors Affecting
1.	Thermal Stability	Thermal Expansion Coefficient of Material Used
2.	Structural Integrity	Uniform Hardness
3.	Ease of Handling	Density of Material
4.	Mitigate measurement effects other than hardware errors	Geometry of Ball Plate
5.	Able to characterize measuring volume	Symmetry of Ball Plate
6.	Enable Self Calibration of CMM	Performance Stability of Artifact

II. ZIRCONIA-DOLERITE BALL PLATE

Innovative Ball Plate is designed and developed, which delivers above six requirements, listed in Table 1. Apart from above attainment of characteristics, the Zirconia-Dolerite Ball Plate is able to measure 19 geometrical errors out of 21 errors specified in ISO standards. These are Linear Displacement errors (All Three Axes), Horizontal Straightness errors (All Three Axes), Vertical Straightness Errors (All Three Axes), Pitch (All Three Axes), Yaw (All Three Axes), Roll (Z Axes) and Squareness Error (All Three Axes).

The actual manufactured photograph showing digits as ball numbers is shown in fig 1.

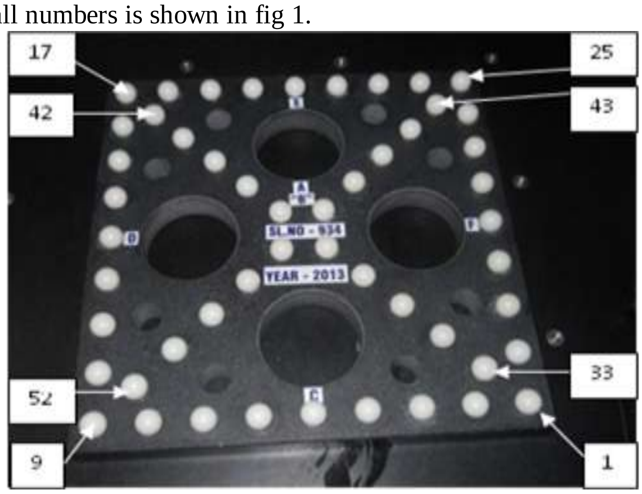

Fig1: Zirconia-Dolerite Ball Plate

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III. GEOMETRY OF BALL PLATE

Ball Details: Material-Zirconia, Diameter – 25 mm, Total Balls used 52

Plate Details: Material – Dolerite (Indian Granite processed at Guindy Machine Tools, India)

Zirconia Balls are Glued to Dolerite Plate by Loctite H3101 Structural Adhesive

IV. DIMENSIONS OF BALL PLATES

Developed Artifact will have to exhibit considerable dimensional stability on entire temperature range and also for a considerable duration before it is calibrated again. A high accurate CMM machine (Laboratory Standard) can be used for comparison of measurement for machine under inspection.

A highly accurate Machine probe SP 80 was used to measure distances of balls under standard metrological conditions of 20^0C and listed in table 2. Same ball plate was then taken to CMM under test and machine was checked in first month for the same distances and also subsequently after 6 months and 12 months.

The resultant measurement results are listed in table 2.

Table 2: Ball Distance

Ball Distance	First Month Distance in (mm)	Sixth Month Distance in (mm)	One Year Distance in (mm)	Difference, D (1-6 Month) mm	Difference D (1-12 Month) mm
1-2	49.9654	49.9695	49.9692	-0.0041	-0.0038000
1-3	99.9061	99.9101	99.9094	-0.0040	-0.0033000
1-4	149.9338	149.9374	149.9366	-0.0036	-0.0028000
1-5	200.1647	200.1681	200.1672	-0.0034	-0.0025000
1-6	250.0814	250.0846	250.0838	-0.0032	-0.0024000
1-7	299.8975	299.9006	299.8995	-0.0031	-0.0020000
1-8	349.8052	349.8082	349.8070	-0.0030	-0.0018000
1-9	399.9123	399.9154	399.9140	-0.0031	-0.0017000
1-25	400.1492	400.1467	400.1458	0.0025	0.0034000
1-26	350.1116	350.1093	350.1086	0.0023	0.0030000
1-27	300.1497	300.1475	300.1469	0.0022	0.0028000
1-28	250.1574	250.1553	250.1549	0.0021	0.0025000
1-29	200.0519	200.0499	200.0492	0.0020	0.0027000
1-30	150.1383	150.1363	150.1357	0.0020	0.0026000
1-31	100.0441	100.0421	100.0417	0.0020	0.0024000
1-32	50.0464	50.0443	50.0439	0.0021	0.0025000
9-10	49.8580	49.8580	49.8580	0.0000	0.0000000
9-11	99.8829	99.8829	99.8828	0.0000	0.0001000
9-12	149.8905	149.8907	149.8904	-0.0002	0.0001000
9-13	199.8033	199.8035	199.8032	-0.0002	0.0001000
9-14	249.9483	249.9485	249.9482	-0.0002	0.0001000
9-15	299.8911	299.8913	299.8910	-0.0002	0.0001000
9-16	349.9368	349.9371	349.9365	-0.0003	0.0003000
9-17	399.8921	399.8922	399.8916	-0.0001	0.0005000
17-18	50.0005	50.0005	50.0005	0.0000	0.0000000
17-19	100.0238	100.0240	100.0238	-0.0002	0.0000000
17-20	149.9551	149.9556	149.9554	-0.0005	-0.0003000
17-21	199.9534	199.9535	199.9530	-0.0001	0.0004000
17-22	249.9106	249.9110	249.9104	-0.0004	0.0002000
17-23	299.8040	299.8041	299.8033	-0.0001	0.0007000
17-24	349.7521	349.7523	349.7515	-0.0002	0.0006000
17-25	399.7637	399.7640	399.7631	-0.0003	0.0006000
1-33	49.9835	49.9834	49.9828	0.0001	0.0007000
1-34	99.9726	99.9726	99.9718	0.0000	0.0008000
1-35	149.9113	149.9112	149.9105	0.0001	0.0008000
1-36	199.8623	199.8625	199.8616	-0.0002	0.0007000
1-37	249.9107	249.9106	249.9096	0.0001	0.0011000
1-38	315.5788	315.5785	315.5777	0.0003	0.0011000
1-39	365.3787	365.3782	365.3774	0.0005	0.0013000
1-40	415.5511	415.5509	415.5500	0.0002	0.0011000
1-41	465.6812	465.6808	465.6798	0.0004	0.0014000
1-42	515.7218	515.7211	515.7201	0.0007	0.0017000
1-17	565.7309	565.7308	565.7292	0.0001	0.0017000
9-52	49.3748	49.3770	49.3760	-0.0022	-0.0012000
9-51	100.0488	100.0513	100.0503	-0.0025	-0.0015000
9-50	149.6783	149.6808	149.6797	-0.0025	-0.0014000
9-49	199.9566	199.9592	199.9579	-0.0026	-0.0013000
9-48	249.5523	249.5547	249.5532	-0.0024	-0.0009000
9-47	315.4193	315.4215	315.4201	-0.0022	-0.0008000
9-46	365.6003	365.6026	365.6012	-0.0023	-0.0009000
9-45	414.8572	414.8597	414.8583	-0.0025	-0.0011000
9-44	465.7893	465.7917	465.7900	-0.0024	-0.0007000
9-43	515.5453	515.5473	515.5457	-0.0020	-0.0004000
9-25	565.4408	565.4405	565.4397	0.0003	0.0011000

The differences in readings should be as minimum as possible, calling for Statistical Performance analysis for checking dimensional stability of Artifact.

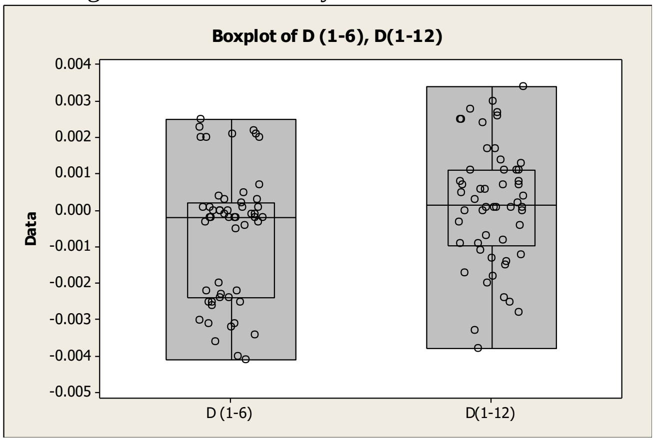

Fig2: Box Plot for differences in 1st and 6th months readings.

The box plot in fig 2 shows minimal differentiation in readings for CMM under test showing, considerable stability of artifact.

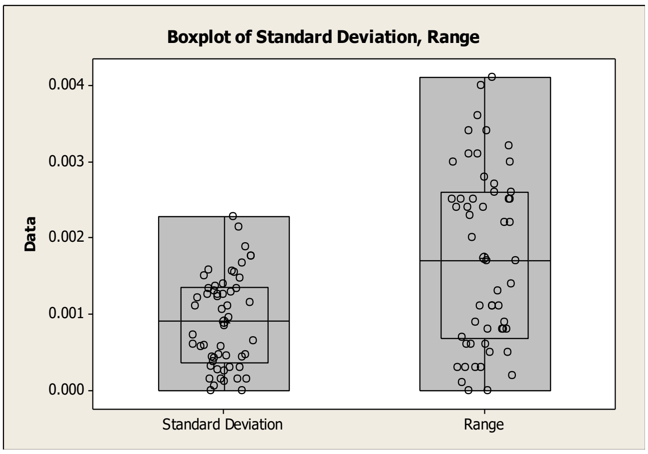

Fig3: Box Plot for Standard Deviation and Range

The maximum standard deviation reported by readings taken in entire year is 2.285μm.

V. STATISTICAL ANALYSIS

A. Run Test

Run Test is used to check randomness of the given data. It is a nonparametric test as population distribution parameters. From this test, determining values above or below mean value if random, can be computed.

Runs test for Mean

Runs above and below K (mean) = 258.951
The observed number of runs = 10
The expected number of runs = 27.6667
24 observations above K, 30 below
P-value = 0.000

As the resulting p-Value (0.000) is smaller than the alpha level of 0.05 (95% Confidence Level), it is concluded that the data are not in random order.

B. 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 is shown in figure 3.

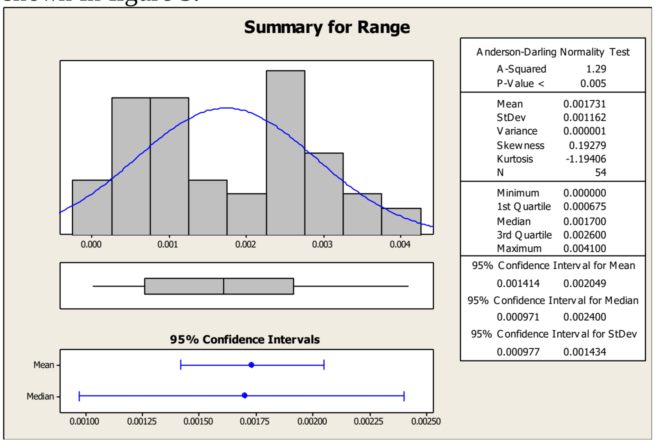

Fig 4: Graphical Summary for Range of (1-12 Month)

The graphical summary also displays a table of Anderson-Darling Normality Tests Statistics used to determine if data follow a normal distribution. If the p-valuve is lower than fixed level of significance, the data do not follow a normal distribution. Here, a significance level of 0.05 is considered.

The Anderson Darling Normality Test (A-Squared 1.29, P-Value <0.05) indicates that data for Range doesn't follow normal distribution curve.

As time-series data violates t-test due to temporal dependency, autoregression (AR) is used accounting for Cross Correlation.

C. Pearson Correlation Coefficient

The relationship between the analyzed series X and Y, correlation coefficient is expressed. Selective co-variance is calculated according to following relationship:

$$C_{xy} = \frac{1}{n-1}\left[\sum_{i=1}^{n} X_i Y_i - n\overline{xy}\right]$$

Where

$X_i Y_i$ - Values of observations

$\overline{x}, \overline{y}$ - Arithmetical averages calculated from the values measured.

If C_{xy} is not zero, the correlation between the series exists and grows further stronger.
If the value of the strength of correlation needs to be determined then the selective coefficient called as Pearson's Correlation coefficient is determined as

$$r_{xy} = \frac{C_{xy}}{S_x S_y}$$

Where S_x and S_y are selective random variance.

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.

D. Cross Correlation

Cross Correlation is used in analysis of multiple time series. It is generalization of standard linear correlation analysis.
To check the consistency of retention of ball plate dimensions, cross correlation method is used with difference (lag of 6 months).
Cross Correlation is the standard method for measuring to what extent the two rows are correlated. Cross correlation r_{xy} with lag d is defined using the following relationship

$$r_{xy} = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)\left(y_{i-d} - \overline{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_{i-d} - \overline{y}\right)^2}}$$

Where lag is to d=1, 2,…n.
The cross correlation function is a convolution of the transfer function with the continuum Autocorrelation function. The CCF depends on the continuum behavior.
For the large-sample normal approximation, a criterion is always used to decide if a specific sample cross correlation is within sampling error of zero. If the population autocorrelation of lag k is zero for k = 1.2, then adequately large n, $r_{xy}(k)$ is approximately normally distributed with mean (μ) zero and standard deviation (σ) is $\frac{1}{\sqrt{n-|k|}}$. It gives same results if the population cross correlation of lag k is zero. Since approximately 95% of a normal population is within 2 standard deviations of the mean, a test that rejects the hypothesis that the population autocorrelation of lag k equals zero when $|r_{xy}(K)|$ is greater than $\frac{2}{\sqrt{n}\sqrt{n-|k|}}$ has a significance level (α) of approximately 5%.
Cross correlation computes and graphs correlations between two time series.

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The correlation graph is plotted as per following.

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Cross Correlation Function: D (1-6), D(1-12)

CCF - correlates D (1-6)(t) and D(1-12)(t+k)

            -1.0 -0.8 -0.6 -0.4 -0.2  0.0  0.2  0.4  0.6  0.8  1.0
            +----+----+----+----+----+----+----+----+----+----+
 -6   0.009                           X
 -5   0.172                           XXXXX
 -4   0.323                           XXXXXXXXX
 -3   0.483                           XXXXXXXXXXXXX
 -2   0.646                           XXXXXXXXXXXXXXXXX
 -1   0.808                           XXXXXXXXXXXXXXXXXXXXX
  0   0.973                           XXXXXXXXXXXXXXXXXXXXXXXXX
  1   0.752                           XXXXXXXXXXXXXXXXXXXX
  2   0.560                           XXXXXXXXXXXXXXX
  3   0.388                           XXXXXXXXXXX
  4   0.240                           XXXXXXX
  5   0.075                           XXX
  6  -0.082                         XXX
```

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 11 month at stretch.

VI. CONCLUSION

The manufacturing and operating cost of this ball plate is considerably low and requires one time setup for entire calibration of ball plate. The Zirconia balls are glued to dolerite plate eliminating the requirement of blind hole in balls, reducing 1/10th of manufacturing cost. The dimensional stability of artifact shows its cost effectiveness.

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