Study of Spindle Rotational Accuracies versus Bore Accuracies on Machined Test Pieces on a CNC Machining Center

Ramesh H. Aralaguppi[1], T. Subramanian[2]

Abstract

Metal Cutting Machine tools are built to have certain geometrical accuracy interrelationships amongst its moving elements since they directly influence the geometrical relationships of machined surfaces on the components machined on them. Typically for a CNC Machining Center for example, the run out of main spindle and geometrical alignment with respect to the Work Table plane as well as movements in X Y Z axes directions are checked as per national and international Test Charts. Allowable Spindle Run Out values are routinely checked as part of standard Test protocols. However it is observed mere Run Out accuracies seen in the traditional method on the Test mandrel are insufficient to predict finish boring accuracies on the work piece. Various factors like the dynamic running accuracies and spindle axis, stability during heating of the spindle bearings and housings, the dynamic unbalance of rotating parts etc finally influence the Bore Accuracies. In this paper, the effect of Dynamic running accuracies of the Main Spindle on the Circularity and Cylindricity of the finish machined bores are studied and interrelationship tried to be established.

Keywords: Machine tool spindle, Rotational Accuracy, and Bore Accuracy.

1 Introduction

Machine Tools are used to remove material from components and produce the required shape and dimensional size with required surface finish at optimum cost. There are different methods in metal removing processes. In this paper the metal removal by Boring Process is studied and analyzed on typical Horizontal Machining Centers (HMC). The quality of the bored component is seen in terms of Circularity, Cylindricity and Surface Finish. These parameters largely depend on the spindle rotational accuracy of the machine tool spindle. To understand the concept of rotational accuracy of spindle, the authors studied and conducted experiments on runout and error motion of the spindle and tried to establish the relationship between rotational accuracies of spindle and bore accuracies on the components.

2 Spindle Rotational Accuracy

In Horizontal Machining Centers, HMCs, like in most of other types of machine tools, assembled main spindles units are routinely inspected for its rotational accuracy. It is understood this is an important factor and efforts are accordingly made to achieve finer run out accuracies through maintaining highest precision on the individual spindle shaft dimensions and geometry, in the selection and fitment of super precision bearings and related spacers, pre loading nuts and other related parts and following careful assembling and testing procedures.

Ramesh H. Aralaguppi.,
Research and Development Center, Bharat Fritz Werner Ltd., Tumkur Road, Bangalore:560022, INDIA,
E-mail: ramesh.a@bfw.co.in

T. Subramanian.,
Research and Development Center, Bharat Fritz Werner Ltd., Tumkur Road, Bangalore:560022, INDIA,
E-mail: subramanian@bfw.co.in

2.1 Runout (TIR)

Measurement of spindle Runout is the classical method of measuring spindle rotational accuracy. Runout is also called Total Indicator Reading (TIR). The runout of machine tool spindle is measured by using precisely cylindrical mandrel. The mandrel is clamped in machine tool spindle taper bore and the spindle is slowly rotated by hand. The runout measurements on mandrel surface are recorded using precise dial gauges placed on machine table. As per Murthy [1], this classical method of measuring spindle rotation error reads pure eccentricity of a reference surface of the spindle while such an eccentricity has really no influence on the error of the workpiece. Mere Runout or TIR as representing Spindle Rotation error is hence defective and inadequate to provide information on the component bore accuracies expected for certain measured levels of classical Run Out figures.

However, in the machine tool industry, generally, the spindle is checked routinely *only* for its TIR values in the classical method.

2.2 Error Motion

Alternately we can subject the spindle to Error Motion Analysis. As opposed to Run out or TIR value, the Error motion is unintended relative displacement in the sensitive direction between the tool and the workpiece. Error motions are specified as location and direction as shown in Fig. (1) and do not include motions due to axis shifts associated with changes in temperature, load or rotational speed.

In ideal condition, the Rotation of spindle axis of centerline would remain stationary or in other words not shift theoretically. But, in practical working situations, the spindle rotational axis of centerline keeps on changing as instantaneous center of rotational axis changes. Hence, three Error Motions exist. They are pure radial error, pure axial error and tilt error. Error motion definitions are referred from ISO 230-7[2].

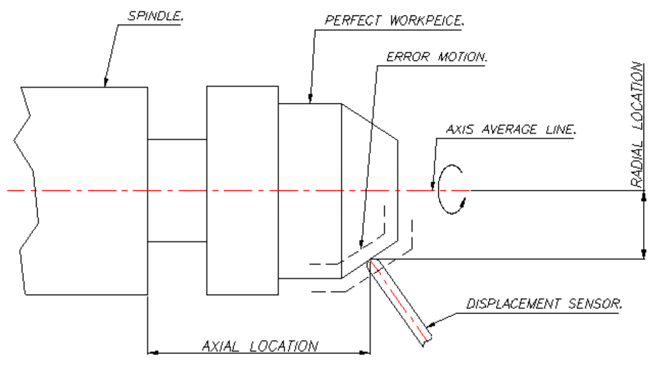


Figure 1: General case of error motion.

2.2.1 Pure Radial error motion

It is defined as motion in which the axis of rotation remains parallel to the axis average line and moves perpendicular to it in the sensitive direction. The sensitive direction is direction perpendicular to the perfect workpiece surface through the instantaneous point of machining or measurement.

2.2.2 Axial error motion

Axial error motion is error motion coaxial with the axis average line. This error motion may be measured as the motions, in the axial direction along the axis average line, of the surface of a perfect flat disk or spherical test artifact with its centerline coincident with the axis of rotation.

2.2.3 Tilt error motion

Tilt error motion is the error motion in an angular direction relative to the axis average line. This motion may be evaluated by simultaneous measurements of the radial error motion in two radial planes separated by a distance along the axis average line.

2.3 Error Motion versus Runout.

Measurement of error motion is different from runout measurement and it is very important to understand the differences. Jemielniak and Chrzanowski [3] explained in their paper that it is important to measure the change of the axis rotation position during rotation at high speeds, because the runout test is conducted at low rotational speed. Spindle running contain both roundness error of spindle and centering error of axis of rotation. Radial Run out (as in the classical method) will be identical to radial error motion ***only*** if both of Roundness Error and Centering Error are removed, Jinho Kim et al [4], David J Whitehouse [5].

To understand these mechanical phenomena, the authors conducted the experiments.

3 Experiments

3.1 Runout Measurement Test

The classical method of spindle runout was conducted on first Horizontal Machining Center (HMC 1). As shown in Fig. (2), the precisely cylindrical mandrel was clamped in the spindle taper bore and the spindle was rotated by hand at low speed with dial gauge sensing against mandrel surface. The total indicator readings of radial runout are listed in Table. 1.

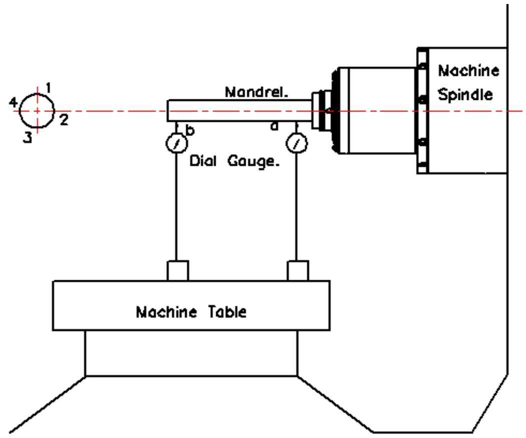


Figure 2: Spindle rotational runout measurement on precise mandrel.

Table 1: Spindle rotational runout readings (HMC 1)

Position of Dial Gauge on Mandel	Readings (μm)			
	at 1	at 2	at 3	at 4
a	0.0	0.5	0.5	0.5
b	3.0	5.0	3.5	5.0

The classical method of spindle runout is conducted on a second Horizontal Machining Center (HMC 2). The total indicator readings of radial runout of the spindle are listed in Table. 2.

Table 2: Spindle rotational runout readings (HMC 2)

Position of Dial Gauge on Mandel	Readings (μm)			
	at 1	at 2	at 3	at 4
a	8.0	8.0	8.0	8.0
b	9.0	9.0	9.0	10.0

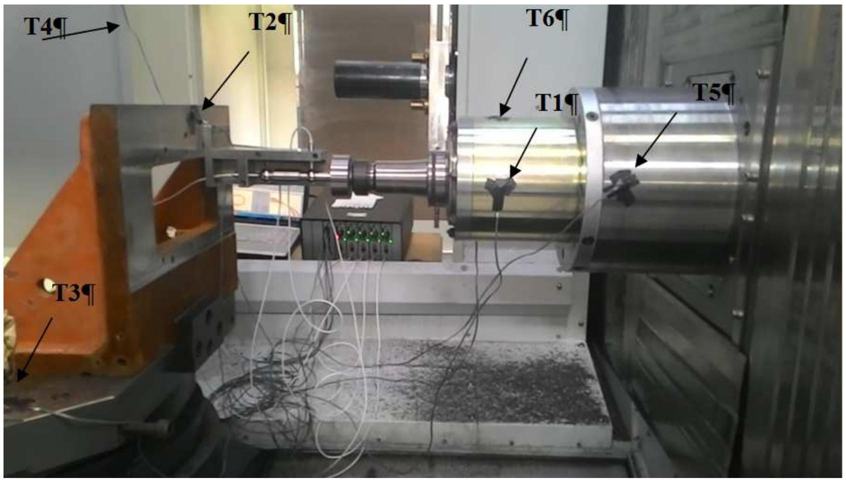
3.2 Spindle Rotational Accuracy by Spindle Running Error Motion test

3.2.1 Methodology

The spindle error measurement setup, with the non-contact sensors mounted in the fixture, as shown in Fig. (3) was used. In this setup, a test mandrel, having two high precision test balls at a fixed distance, is mounted in the machine spindle. The test procedure as prescribed by ASME B5.54-2005, described below, was used.

- Spindle was warmed up for 10 min @ 75% of maximum speed before starting data collection for spindle evaluation
- Probe was set-up as per ASME B89.3.4M guidelines
- Data was collected for 30 revolutions

- Radial error (total, average and asynchronous) and axial error (asynchronous and total error) were computed
- Tilt error (synchronous, asynchronous and total) was computed with the help of simultaneous measurement of radial error at two points separate by 76.2mm



T6

Figure 3: The HMC spindle error measurement setup

1

3.2.2 Thermal stability test (Spindle warm up test and transient shutoff test) as per ASME B5.54-2005

The test was carried out on the spindle of the Machine to identify the effects of internal heat generated by rotation of the spindle and the resultant temperature gradients on the distortion of the machine structure. The machine was stabilized overnight to stabilize the effects of internal effects and measurements were started from the cold state. The probe setup is same as per spindle error test. The temperature sensors were mounted on spindle housing near front, on fixture end, on pallet, on spindle front (X Direction), on spindle front (Y Direction) & ambient to measure the temperature drifts.

The following instruments were used for the measurements

1. Lion Precision 5 Channel Spindle Error Analyzer
2. M22-5 Modular system DMT22
3. Capacitance Probes Model: C1-C W/LEMO
4. Temperature Sensors-Thermistors.
5. Master Ball Dual 1”
6. Probe Nest – 5 probe

The spindle was run at 6000 rpm and the measurements were taken for almost 4 hrs of spindle running. The thermal drift was computed. The spindle was shutoff and the data was collected for 20 minutes with the same setup. The change in spindle centre shift with respect to the time from the cold start in radial direction at 6000 rpm is presented in Table 4 and Fig. (4). The spindle error rotation values (Radial, axial and tilt) with respect to the time from the cold start is depicted in Table 5. The obtained thermal stability plots are depicted in Fig. (5).The obtained spindle drift x, y, z direction in terms of micrometers are tabulated in Table 3.

Table 3: Temperature sensors temperature and thermal drift readings.

SL. No.	Temperature Sensor	Rise in Temperature (°C)
1.	On Spindle front X Direction (T1)	2
2.	On Fixture End (T2)	1
3.	On Pallet (T3)	1
4.	Ambient (T4)	3
5.	On Spindle Housing (T5)	3
6.	On Spindle front Y Direction (T6)	2
Temperature Drift in X,Y,Z Direction and X_2 Drift		
SL. No.	Direction of Drift	Drift (μm)
1.	X-Drift	8.19
2.	Y-Drift	19.7
3.	Z-Drift	21.6
4.	X2 -Drift	10.5

Table 4: Change in Spindle centre shift with respect to the time from the cold start in radial direction at 6000 rpm

Time Min	X drift (μm)	Y drift (μm)	Z drift (μm)	X_2 drift (μm)
30	3.85	3.71	9.62	3.94
60	5.04	6.81	11.60	5.30
90	5.85	9.41	11.60	6.48
120	6.46	12.20	11.60	7.54
150	7.01	14.40	11.60	8.78
180	7.44	16.50	11.60	9.90
210	7.44	18.20	14.30	9.90
226	7.65	18.60	15.20	10.50

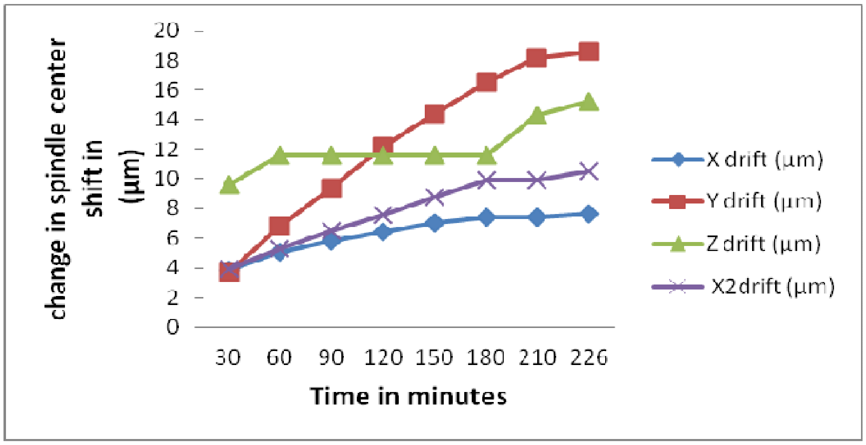
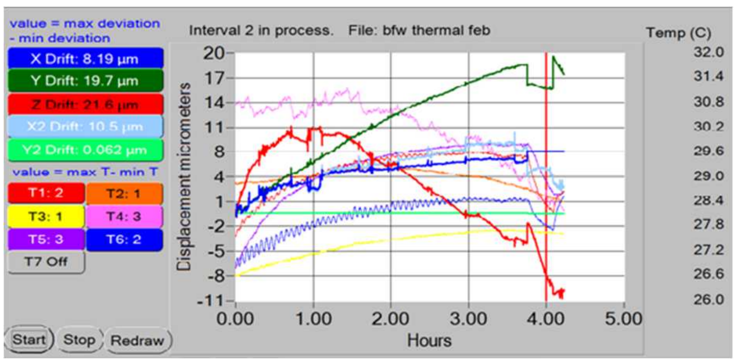


Figure 4: Change in spindle centre shift with respect to the time from the cold start at 6000 rpm

Table 5: Spindle error rotation values (Radial, axial, and tilt error) with respect to the time from cold start at 6000 rpm

Time in min	Radial (µm)			Axial (µm)		Tilt in (µ radian)		
	Sync.	Async.	Total	Async.	Total	Sync.	Async.	Total
30	0.31	0.51	0.73	0.50	0.91	3.73	13.36	14.80
60	0.34	0.54	0.74	0.51	0.88	3.60	11.84	14.68
90	1.64	0.47	1.80	0.53	0.91	18.94	12.39	27.67
120	1.66	0.54	1.89	0.47	0.79	19.81	11.68	28.51
150	1.88	0.65	2.05	0.52	0.88	23.04	12.19	32.04
180	2.01	0.57	2.33	0.50	0.85	24.50	10.32	31.58
210	1.96	0.52	2.27	0.46	0.82	23.94	11.99	34.05
226	2.00	0.53	2.28	0.59	0.82	24.34	11.76	33.48

Figure 5: Thermal Stability Plot (X and Y axes) at spindle speed of 6000 rpm



3.2.3 Observations: Spindle Error Measurement

1. The maximum total radial error of 0.75 µm was noticed at 6000 rpm with asynchronous error of 0.52 µm and synchronous error of 0.28 µm contributing to it.

2. The maximum total axial error of 0.96 µm was noticed at 6000 rpm of which contribution of asynchronous error was 0.49 µm.

3. The maximum total tilt error of 14.17 µ radian was noticed at 6000 rpm with asynchronous error contributing 12.16 µ radian.

3.2.4 Thermal stability test.

1. Thermal drift of the order of 8.19 µm was observed in X direction and this drift stabilized after 3 hours.
2. Thermal drift of the order of 19.70 µm was observed in Y direction and this drift did not stabilize even after 3 hour 30 minutes of running of the spindle.
3. Thermal drift of the order of 21.60 µm was observed in Z direction and the drift has stabilized after 1 hour of running. The drift was positive up to 1 (one) hour and afterwards the drift direction reversed and further drift in negative direction was observed.
4. The maximum temperature rise of about 3°C was observed at the spindle housing.

4. Bore Accuracies On Machined Test Pieces.

The boring test was conducted on HMC-1, on which the spindle runout and error motion test were conducted. The boring test was conducted on three different materials and the circularity, cylindricity and surface roughness of machined test pieces were measured. These results are tabulated in Table 6. Circularity and cylindricity of the bores were measured using Coordinate Measuring Machine (CMM). While conducting the boring test dimensional tolerances were not considered.

Table 6: Measured accuracies and finish on trial components.

SL. No.	Material	Bore Dia. (mm)	Bore depth (mm)	Max. Circularity (µm)	Cylindricity (µm)	Surface Finish (Ra)
1	Cast Iron FG260	30	50	6	10	1.2
		50	75	3	8	1.9
		75	50	3	8	2.1
2	Steel CK45	50	50	3	3	1.2
		40	75	2	2	0.9
		54	50	3	3	1.3
3	Aluminum AL6061T6	30	50	3	4	2.2
		49	50	5	6	2.1
		53	75	4	5	1.8

The boring test on HMC-2 was conducted with test piece of Cast Iron only. Only cylindricity of the test piece is tabulated in Table 7.

Table 7: The values of boring trials on test pieces

SL. No.:	Material.	Bore Dia. (mm)	Bore depth (mm)	Cylindricity (µm)
1	Cast Iron FG260	43	60	4
2		43	60	6
3		43	60	5
4		43	60	6
5		43	60	4
6		43	60	4

5. Conclusions

The paper is basically focused on the relation between Spindle Running Accuracy and the achievable Boring Accuracy on bored test work pieces.

From the experimental data from HMC-1, it is observed that the runout and error motion rotational accuracy of spindle are 5 µm and 2.28 µm respectively. On bored components, the maximum circularity and cylindricity are 6 µm and 10 µm respectively.

From the experimental data from HMC-2, it is observed that though the runout of spindle is much higher at 10 µm, on the bored component, the maximum Cylindricity is only 6 µm.

We can conclude TIR Run out measurement is not a dependable indicator to predict effectively the achievable bore accuracy.

Though in the present experiment, Spindle Error Motion accuracy has been recorded after reaching thermal stability, many factors other than thermal stability of the main spindle characteristics seem to be involved in relating to resulting Circularity and Cylindricity bore accuracies on machined components. Further we can observe for the Spindle Accuracy measurements discussed, both the TIR as in classical method or the Spindle Error Motion Analysis are measured under ‘‘no-load’’ condition. As per Ke Wang et al [6], it is very likely the error motion of the machine tool spindle during the machining process will be different from those in free rotation.

Further experimentation, investigations and analysis are required to conclusively establish a relationship between the Spindle rotational accuracies and resulting bore accuracies.

References

[1] R L. Murthy, 1996 "Spindle Rotation Accuracy and Test Methods for radial spindle rotation error : Precision Engineering in Manufacturing". Text Book, Pages:12-19.

[2] ISO 230-7, "Test Code for Machine Tools". Part 7, "Geometric accuracy of axes of rotation", November 2006.

[3] Krzysztof Jemielniak. and Jaroslaw Chrzanowski, "Spindle Error Movements Measurement Algorithm and New Method of Results Analysis"., Journal of Machine Engineering, Vol. 15, No.1, 2015

[4] Jinho Kim, Dongik Shin, Deokwon Yun, and Changsoo Han., 2007. "The Analysis of Radial/Axial Error Motion on a Precision Rotation Stage". International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering Vol:1, No:5

[5] David J Whitehouse, Handbook of Surface and Nanometrology, 2003; Institute of Physics Publishing, Bristol and Philadephia. 2003

[6] Ke Wang and Edward Morse, Correlation of Spindle Errors to Piece Part Accuracy; University of North Carolina Publication.