# APPLICATION OF A BALLBAR FORDIAGNOSTICS OF CNC MACHINE TOOLS

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This paper describes the possibilities of using the Ballbar QC20-W diagnostic tool for long-term monitoring of geometrical accuracy of CNC machine tools. By introducing regular checks, the production capability and the planned machine maintenance should be increased. The publication presents the results obtained from a case study. The case study describes the procedures and results of introducing a regular inspection into the manufacturing process at the MCV 754QUICK (KOVOSVIT-MAS) three-axis machining center are presented to use statistical tools for long-term machine condition monitoring.

**KEYWORDS**

machine tool, diagnostic, geometric accuracy

## 1 INTRODUCTION

Ensuring production quality with an emphasis on zero defect production places ever-increasing demands on the introduction of diagnostic systems into production. These systems are intensively developed into areas of predictive maintenance, continuous improvement and process monitoring.

The access to the scan tool selection and the measurement time interval will depend on the type of parameter under consideration. Depending on whether it is a slow drift or a chatter.

For CNC machine tools are distributed errors on errors from [Ramesh 2000A, Ramesh 2000B, Okafor 2000]:

- geometric and kinematic errors,
- temperature errors,
- dynamic errors,
- errors from the control system,
- errors due to load.

These errors affect the resulting manufacturing accuracy by only 25%. Errors resulting from errors are also reflected in the resulting manufacturing accuracy [MAREK 2017]:

- machine operation 20%,
- machined parts 5%,
- environment 20%
- measuring 15%,
- working accuracy of machine 25%,
- production technology 15%.

They included errors in the [Ahn 2000], which have a very slow response to so-called quasi-static errors. These quasi-static errors can be attributed to machine geometry and kinematics errors.

The use of the diagnostic system for monitoring the condition of the machine and its capability includes a wide range of activities and the individual types are based on the monitored quantity (Figure 1). From Bearing State, Gear, Lubrication, Cooling, Safety, Precision, Tools, Consumption, etc. [Breze 2014, Huzlik 2014, Hadas 2014, Blecha 2011, Kutalek 2015, Holub 2018]. After identifying an error, it is necessary to move to measures that ensure that the same or better value of the parameter under consideration is achieved. A very often controlled feature of the machine is its geometric accuracy and, in particular, the accuracy of the positioning of the controlled axes [Marek 2009] or also the volumetric precision which describes the more geometrical errors of the machine tool [Holub 2015].

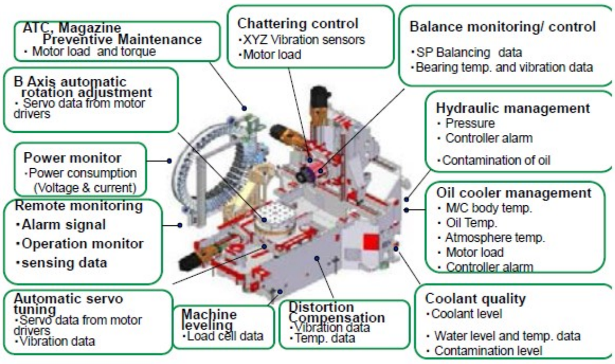


**Figure 1.** Sensingapplicationexamples [Fujishima 2017].

On machine tools used in series production or in piece production with high added value of a future product, the user cannot afford the production of a not good part or an unplanned shutdown of the machine. Thus, the full range of machine-specific diagnostic tools and production technology are used. One of these tools that can be deployed to monitor the condition of the machine, the device Ballbar. The Ballbar is able to evaluate both slow and fast events, which are then reflected not only in the surface quality of the workpiece but also in its length and shape tolerances [USOP 2015]. In the following part of the publication, attention will be paid mainly to quasi-static errors.

## DIAGNOSTIC OF MACHINE TOOL WITH BALLBAR

Diagnostics of machine tools can effectively apply predictive maintenance features. Diagnostic procedures, however, must be fully supported by both the company and the individual workplaces.

### *1.1 Ballbar QC20-W*

The Ballbar QC20-W Diagnostic System has been designed for regular and fast checking of CNC machine tools. The test is based on the principle of circular interpolation and is based on ISO 230-4. The device also includes expert software that helps in evaluating geometric and dynamic machine errors. These errors include position tolerances, circularity, squareness, straightness, relative displacement error, servo delay, cyclic error amplitude, and more.

Expanded Uncertainty (k=2) is given by the equation [Renishaw 2013]:

$$U_{(k=2)} = 0.70 + 0.30\%L \quad \mu m \tag{1}$$

where L is a radial variation (range). That is, for a MCV machine, a radial variation of 10 µm can be obtained. Upon arrival, the expanded uncertainty for Ballbar QC20-W is ± 0.73 µm.

Due to the sufficient number of measured values and knowledge of the machine and the manufacturing process, it is possible to design a procedure for introducing the diagnostic system into regular inspection.

### 1.2 Implementation of a new process in production

On the basis of a successful assessment of the condition of the machine, a request was made to introduce a regular maintenance check process and also be transferable to other machine tools.Introducing a new business process is in itself a complex, technical and managerial task that requires system approach, experience and overview of quality management requirements. The issue of quality management and process management methods is addressed by the ISO 9000 international standard. In particular, EN ISO 9001, which describes the quality management criteria, and which is the only one in this series of standards to be certified.

## 2 EXPERIMENTAL

The publication presents the results of the milling machining centers using Ballbar QC20-w.

### 2.1 Demonstrator

The case study was conducted on the MCV 754QUICK, KOVOSVIT-MAS (Fig. 2)

**Figure 2.** Machiningcentres,MCV 754QUICK, KOVOSVIT-MAS.

MCV 754QUICK (MCV) is a three-axis vertical machining center with kinematics W-X-Y-Z-T. The diagram of the MCV is shown in the following figure 2 on the right. The machine is fitted with a cross table (X, Y axis) and a headstock (Z) with a travel on the stand. The tool magazine is attached to the stand at the same time. This concept is very prone to X and Z axis crossings due to changing machine geometry.

In Table 1 are shown the technical parameters of the MCV, which were part of the delivery protocols for new machines according to ISO 230-2 and ISO 230-4.

**Table 1.** Machine Parameters

| | Positioning[mm] | Repeatability [mm] | Circularity [mm] |
|---|---|---|---|
| MCV 754 QUICK | 0.012 | 0.005 | 0.014 |

### 2.2 Measurement strategy

Test conditions for MCV is described in Table 2.The Ballbar setup was scheduled for a specially-controlled control palette with a Ballbarfitting for the MCV (Fig. 3) machine was attached directly to the machine's work table. All X-Y planes in the range of 360 °, Z-X and Y-Z were tested again in the 220 ° range.The shortened test range from 360 °to 220° was chosen because of the constraint of the machine. A full test would cause a collision between the spindlestock and the Ballbar measuring device.

The test is scheduled for long-term circularity monitoring. The first measurement set consists of 14 cycles when the machine was measured in a non-volumetric state. Volumetric compensations were then activated and further monitored within a range of 9 cycles.

**Table 2.** Circularity test conditions

| | MCV 754 QUICK |
|---|---|
| Axis range X / Y / Z[mm] | 754 / 500 / 550 |
| Spindleorientation | Vertical |
| Feedrate [mm/min] | 4000 |
| Radius [mm] | 150 |

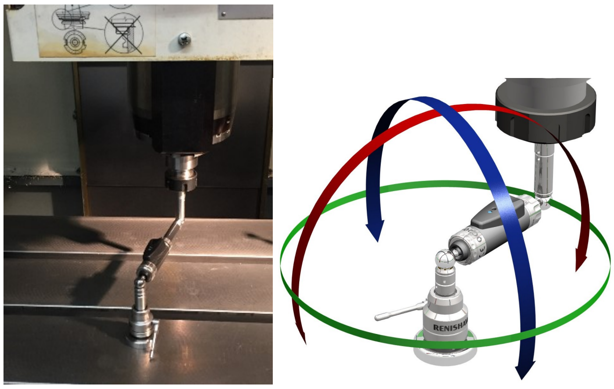

**Figure 3.** Ballbarmount – left, Ballbarscheme- right[Renisahw]

Fig. 4 shows the evaluation of the circularity test performed on the uncompensated and compensated MCV 754QUICK. From the analysis we can find that the dominant error is the "Scaling mismatch" error. This error accounts for 27% of the total circle error, which is equal to 9.6 ± 0.73 µm (Fig. 5 - up, test nr. 14). The second circle affecting the resulting circularity is the "reversal spikes" error in the Y axis, which accounts for 24% of the circularity error. Another error is Squareness, which has a 15% share of the circle error. As can be seen, both geometric and dynamic machine errors can be assessed. The circularity error for compensated machine is equal 8.0 ± 0.72 µm (Fig. 5 - down, test nr. 9).

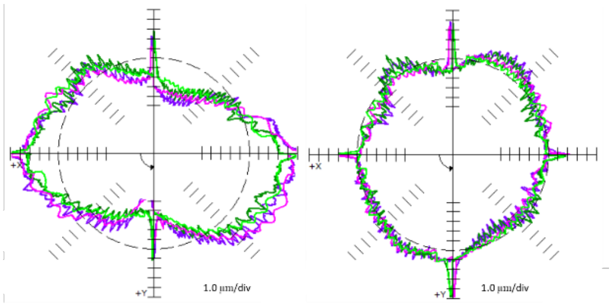


**Figure 4.** Resultsofthe test XYplane, compensationoff – left, compensation on – right.

As described above, the results for MCV machine were obtained at all planes. The data was subsequently processed to assess the machine's capability and to introduce a circular interpolation test into the production process.

### 2.3 Case study – Statistical data processing

In order to be able to deal with the eligibility indicator, it is necessary to verify the normality of the data. The normality test forXY planewithout compensation and XY with compensation was performed according to the Anderson-Darling test. On the basis of the processed test it can be argued that the data on the XY plane without compensations does not come from the normal distribution (Figure 5 at the top) and in the XY plane with the compensations (Figure 5 below) they have the character of normal distribution. A Grubbs test was then carried out to remove a 14.6 µm offset at the XY plane without compensation. A 14.6 µm error was caused by a CNC program error and a bad correction table created for a different machine state. In a non-matching combination, the error then increased by about 5 µm.Verification of the normality of data, which has already confirmed that the data comes from a normal distribution, followed.

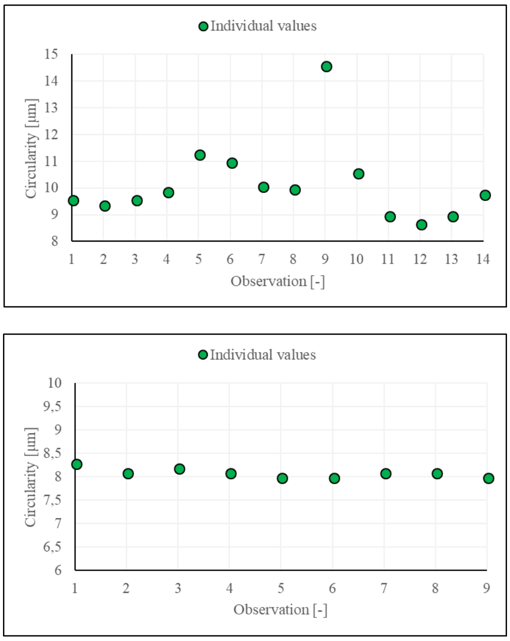


**Figure 5.** XY Circularity Test Results, MCV754 QUICK, Without Compensation - Up, With Compensation – Down.

The next step was to calculate the eligibility and determine the tolerance limit of the circularity. The upper specific limit (USL) is further calculated according to the following formula:

$$C_{pk} = \frac{USL-\mu}{3\sigma} \tag{2}$$

$$USL = \mu + (3\sigma \cdot C_{pk}) \tag{3}$$

where $\mu$ and $\sigma$ were obtained from the Minitab Software and the $C_{pk}$ value was 1.67. For the XY plane, the results in Table 3 are shown for the option with volumetric compensations switched off or on.Volumetric compensation is based on LaserTARCER measurements with Full rigid body (FRB) and activation of the VCS A3 option for the Siemens Sinumerik 840D sl[HOLUB 2014].

**Table 3.**Calculated USL values

| Plane | Compensation | $C_{pk}$ [-] | µ [µm] | σ [µm] | USL [µm] |
|---|---|---|---|---|---|
| XY | OFF | 1.67 | 9.75 | 0.722 | 13.37 |
| XY | ON | 1.67 | 8.10 | 0.1 | 8.60 |
| YZ | OFF | 1.67 | 11.22 | 0.286 | 12.65 |
| YZ | ON | 1.67 | 6.99 | 0.191 | 7.94 |
| ZX | OFF | 1.67 | 13.73 | 0.254 | 15.00 |
| ZX | ON | 1.67 | 8.08 | 0.220 | 9.18 |

Figure 6 shows the measured values, including the calculated upper limit for plane XY. The USL value can be shifted for XY plane by a suitably selected compensation of 13.37 µm to 8.60µm.

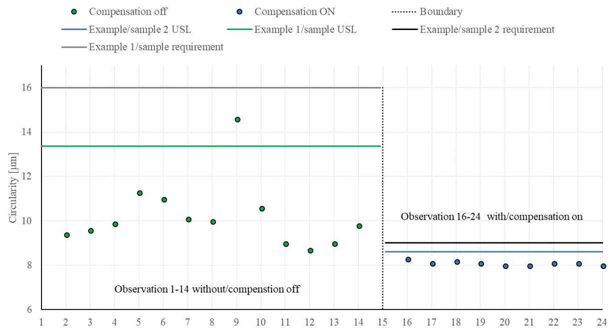


**Figure 6.** Final evaluation of USL plane XY.

Figure 7 shows the measured values, including the calculated upper limit for plane YZ. The USL value can be shifted for YZ plane by a suitably selected compensation of 12.65 µm to 7.94µm.

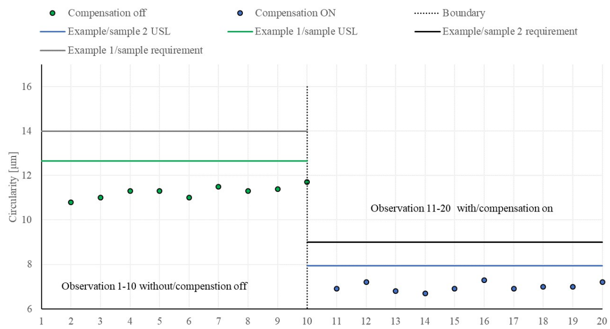


**Figure 7.** Final evaluation of USL plane YZ.

Figure 8 shows the measured values, including the calculated upper limit for plane ZX. The USL value can be shifted for ZX plane by a suitably selected compensation of 15.00 µm to 9.18µm.

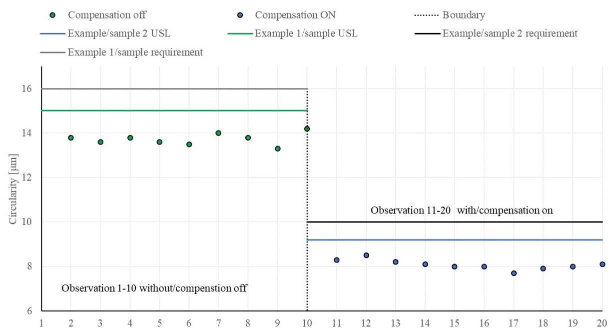


**Figure 8.** Final evaluation of USL plane XZ.

### 2.4 *Case study - Implementation of a new process*

The introduction of a new manufacturing process can be addressed through various quality management tools. To implement the machine tool control process using Ballbar, it was chosen as a turtle tool.

Turtle Diagram is a quality management tool that serves to visualize the process and its particularities. Its advantage is an immediate overview of inputs and outputs. Therefore, it is often used by organizations to define new processes, control existing processes, and audit them. [Blackmores 2018]

The ISO 9001 standard does not directly require the use of the turtle diagram but in Chapter 4.4.1 it states: "The organization must identify the processes needed for the quality management system, their application throughout the organization, and a) determine the inputs and expected outputs of these processes" [ISO 9001]. Furthermore, the ISO

9004 standard in Chapter 7.2 states: "In the process of planning and management, the following issues should be considered: - the objectives to be achieved, - the inputs and outputs of the process, - the resources and information, - the activities and methods" [ISO 9004]. For these purposes, the turtle chart is used.

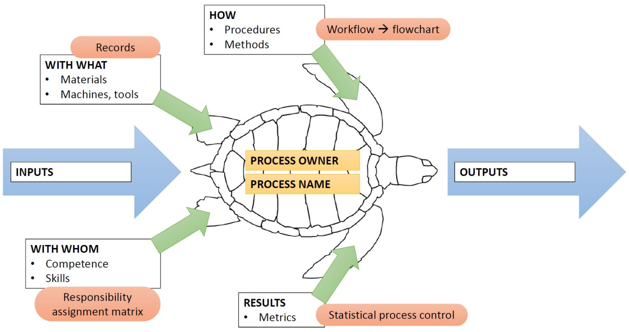


**Figure 9.** Scheme turtle diagram for the implementation of a new process of production.

Inputs can be characterized as recurrent costs of the process. The inputs include material (consumables, connecting, assembly, logistics, office, etc.) and costs associated with the process (rental of production areas, wages, energy, etc.). Process costs and requirements are described in the "What" tab. Most often, machines, tools, handling and warehousing equipment, etc., are needed to ensure the process.

The outputs can be divided into the desired and secondary ones. Required outputs include primarily objects or services that are the goal of the process. Outputs arising from production (unused material, used packaging material, waste water, etc.) are among the secondary ones. A positive assumption of processes for top management is the positive ratio of inputs to outputs (from the financial point of view). The "Who" tab - within the process, it is necessary to define who will do and answer for what activities. This can be effectively used by the responsibility matrix. In addition, it is necessary to specify the requirements for the personnel, ie the required skills, professional competence, certification, etc. "How" - it is also necessary to define how to proceed in the creation of the intended goal. At the level of middle management, this means primarily the definition of workflow - the description of the sequence of activities. You can use the flowchart diagram to do this. At the production level, it is necessary to ensure drawing documentation, assembly instructions, etc. "Results" - in order to control and evaluate the process, it is necessary to define measurable (quantitative) indicators - or metrics and to determine how they will be measured and recorded. This area is mostly responsible for quality departments in industrial plants and provides, among other things, gauges, calibration, records, etc. From a process point of view, SPC is used.

Based on the production specification, process boundaries were determined in an expert manner. The level of straightness error (Fig. 10) of ± 4µm / m and the upper limit ± 6µm / m and the squareness(Fig. 11) of ± 4µm / m and the upper limit ± 6µm / m have been determined as the upper warning limit.Based on the findings from Chapter 2.3, the implementation of new measurement that is focused only on errors squareness and straightness. Measured in time machined March 16, 2018 - April 27, 2018 and the machine was controlled in the range of seven.All measurements were made in a state without activated compensation.

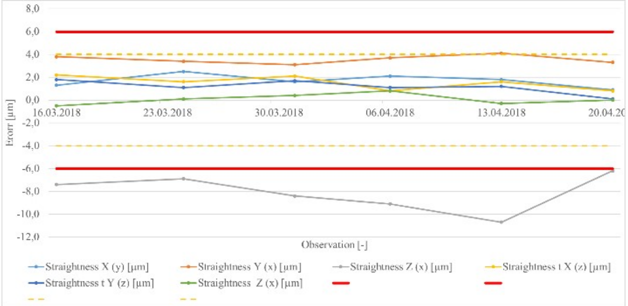


**Figure 10.** Results of straightness errors.

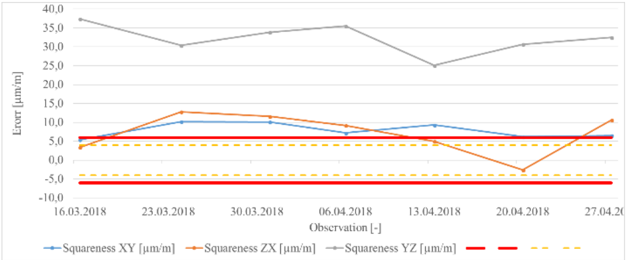


**Figure 11.** Results of squareness errors.

On the basis of the measured and evaluated data, appropriate measures were also proposed to ensure that the assessed values are kept within the specified limits.From long-term observation, it can be seen that no local deflections of straightness or squareness are evident (Fig. 10). In addition to astraightness EZX error, the directness values are in the limit, and it is up to the person to be confronted with the need for a correction of this error or not. Furthermore, it can be seen from the results of the squareness error that none of the monitored parameters is in the tolerance and the intervention is necessary (Fig. 11). On the basis of this data, it is possible to choose a good type of compensation, which is undoubtedly a volumetric compensation, but it is also possible to use the standard compensation for eliminating only squareness errors. This solution will be time and cost effective if we only compensate for squarenesserrors.

## 3 DISCUSION

Establishing a USL (upper specific limit) for long-term production assessment can be a tool to ensure long-term manufacturing precision or as an incentive to increase manufacturing accuracy. The limit setting (USL) remains on the machine user, that is experience and subjective judgment.

During the implementation of Industry 4.0, it can be expected that based on data processing from workpiece control, environment, work conditions, and machine diagnostics, the solution described above will have good conditions for its application in industry. A prerequisite for the deployment and further development of this application is the development of AI (Artificial Intelligence) and M2M (Machine to Machine) communications.

Another task for processing is to determine the machine inspection interval with respect to the surrounding conditions or the seasons when the geometry accuracy of the machine can be changed. A prerequisite for addressing these tasks is the introduction of regular control in the production process with the Ballbar QC20-w diagnostic device or the like.

## 4 CONCLUSIONS

The publication describes the use of Ballbar QC20-w for regular control in the production process, including a proposal for a process for its introduction into the production process. Statistical tools such as normality tests, remote values tests, control diagram, necessary for further processing of measured and evaluated data are described here. These tools and procedures can be applied to any diagnostic system working on circular interpolation tests.

By introducing control processes, you can obtain sufficient information to learn the production process and to introduce predictive maintenance. In order to use these data, they must undergo statistical processing in order to distort the measured data affected by the ambient conditions.

The information thus obtained will be further used for subsequent analyzes related to workpieces and their manufacturing tolerances.

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