Measurement uncertainty associated with the performance of the machine tool under quasi-static loaded test condition

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Abstract

For the proper characterisation of different physical quantities in machine tools, it is obligatory to report the uncertainties connected to the measurements. The uncertainty evaluation according to international standards expresses information of the quality and the reliability of the measurement result. Applications like calibration and compensation are sensitive for the quality of the input data, thus the reliability of the characterisation results need to be interpreted accurately to avoid significant residual errors. General approaches take several factors into consideration during the estimation of measurement uncertainty such as the environmental variations or the uncertainties of the measurement device or the setup. At the same time various repeatable and non-repeatable sources due to the behaviour of the machine tool during the test execution are ignored.

This paper highlights the significance of the uncertainty sources connected to the performance of the machine tool itself under quasi-static and loaded condition. The variation of the static stiffness of machine tools, the hysteresis and the play in the system can be even more significant uncertainty sources than the above mentioned ones. Under the framework of Elastically Linked Systems (ELS), a circular test device the loaded double ball bar (LDBB) is used in a case study to identify this effect. The LDBB can be used as a double ball bar and it also enables the measurement of machine tool deflections under quasi-static load. A measurement methodology is proposed to properly describe and demonstrate the variation of the contributing uncertainties associated with repeatability performance of the machine tool. With this approach important interdependencies can be expressed as uncertainty sources and the reliability of the measurements can be increased.

1 Introduction

Testing the positioning performance of numerically controlled machine tools means the determination of the accuracy and the repeatability under predefined conditions. The fundamental aim of these approaches is to describe the relative displacement of the component that carries the work-piece with respect to the component that carries the cutting tool. Test methods are dedicated to measure systematic and random contributors of this displacement (error), to help the evaluation and the improvement of the positioning performance in case of real cutting conditions. In this assessment the concept of measurement uncertainty can be used to establish a common base between systematic and random errors supporting their characterisation.

It is well-known that the measurement result is influenced by variations, caused by changes in the environment or the measurement itself. The conclusions on these variations made it obvious, that no measurement result can be complete without the statement of the connecting uncertainties. Thus the measurement uncertainty can be seen as a quantification of the reliability of the measurement based on available information and necessary assumptions. In the end the considered contributors and their expressed magnitudes will strongly define the measurement uncertainty [1]. Uncertainty statements in machine tool testing generally lack the consideration of the influence factors coming from the machine tool itself. B. Bringmann and W. Knapp [2] introduced on systematic errors, that the unloaded geometric test uncertainty depends on the machine tool performance. The main characteristic that affects the test results in this case is the interdependency between the geometric error sources, which after further measurements and considerations can be part of a type B uncertainty evaluation. In case of unloaded testing the type A evaluation consists valuable information on the repeatability of the machine tool (as a contributor summarizing the random error sources of the machine tool), but it is a demanding task to separate from other random contributors.

This paper presents that the measurement uncertainty depends on the performance of the machine tool under loaded test condition. In this manner the measurement uncertainty is not just a quantification of the reliability of the measurement, but characterizing the reliability of the machine tool as well. Loaded testing is characterizing the capacity of the machine to endure loads, in the quasi-static case this means the static compliance and hysteresis of the machine tool. In contrast with the unloaded case the focus of the dependency is not on the systematic, but on the random errors, affecting the repeatability of the machine tool. With special focus on the type A uncertainty evaluation this dependency will be quantified. Furthermore a measurement process is proposed according to the findings of the framework of the Elastically Linked Systems.

The proper characterization instrument has a central role in this approach. A circular test device the loaded double ball bar (LDBB) is used to demonstrate the aforementioned dependency. The LDBB can be used as a double ball bar and it also enables the measurement of machine tool deflections under different load levels along the circular trajectory.

2. Machine tool testing under quasi-static and loaded conditions

Testing of numerically controlled machine tools integrate deep understanding of state of art knowledge on machine tools and metrology. Thus tendencies in both research areas should influence the procedures applied in testing. ISO 230-1 [3] specifies methods for determining the accuracy of machine tools with no-load or under quasi-static operational conditions. The goals of these tests are to discover potential geometric and quasi-static load induced errors which can affect the relative motion of the workpiece and the cutting tool.

This paper focuses on the quasi-static loaded testing, thus the static compliance characterisation of machine tools. The static compliance can be defined as a “linear (or angular) displacement per unit static force (or moment) between two objects, specified with respect to the structural loop, the location and direction of the applied forces, and the location and direction of the displacement of interest” [3]. However it is widely accepted, that the compliance (according to the previous definition) is a function of the direction of the applied force and the position of each axis, existing international standards do not provide direct guidelines for testing the related variations. The reasons can be found in the lack of proper instrumentation, which is usually limited to the measurement of displacement in one position and direction for one setup, neglecting the characterisation of the machine tool`s response in the whole workspace. A circular test device, the Loaded Double Ball Bar (LDBB) [4] facilitates this investigation by measuring the deviations at different load levels, positions, directions and feed rates. This device (Figure 1) was used to support the establishment of the Elastically Linked System concept to associate the machining system capability to the machined part accuracy level [5].

The focus of this paper is not the systematic variation of the static compliance, but the repeatability response of the machine tool for loaded condition, which is observed through the measurement uncertainty and usually cannot be directly separated, especially in case of an indirect measurement method. It is well known, that deflections of the machine tool due to quasi-static loads have a strong influence on accuracy, where the correlation is negative, so higher load resulting lower accuracy. This paper is aiming to prove that precision wise, this correlation is positive, so the machine tool response for higher quasi-static load is a higher repeatability.

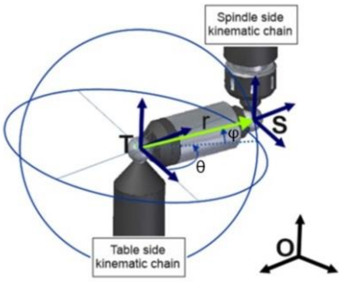

Figure 1: The concept of the LDBB measurement

2.1. Expression of uncertainty in machine tool testing (under quasi-static loaded condition)

In this paper the term measurement uncertainty will be used according to the definition of VIM [6]: “non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used”. GUM [7] provides an internationally accepted procedure that can be used for the estimation of measurement uncertainty, with a high attention on the evaluation of the uncertainty components. Two main approaches have been distinguished: the type A evaluation method for the evaluation of uncertainty by statistical analysis of series of observations; and the type B method for the evaluation of uncertainty by means other than the statistical analysis of series of observations.

Furthermore the GUM highlights the importance of the clear understanding of the measurand. The proper measurement result on the static compliance of machine tool need to express the (1) measured compliance, (2) the statement of the measurement uncertainty, (3) the magnitude of the applied force, (4) the direction of the applied force and (5) the location of the applied force. Otherwise through a type B uncertainty evaluation process point (3-5) shall be included in the measurement uncertainty statement. This type B evaluation requires the compliance characterisation at various positions and directions, and also indicating the linearity (as a possible uncertainty source) on different load levels.

ISO 230-4 [8] describes circular unloaded kinematic tests with the involvement of several error sources measured simultaneously. The main test uncertainty contributors are:

1. the measurement uncertainty of the test equipment;
2. the repeatability of the machine tool, checked by repetition of circular test;
3. the temperature drift of the machine tool and/or the test equipment.

For loaded conditions the following contributors can be added:

4. uncertainty in the level of the applied force
5. setup stability, including internal vibrations transferred through the mounting of the instrument (due to the fact that the positioning is executed under load)

2.1.1. Type A evaluation of measurement uncertainty

The approach which utilizes statistical analysis of measured quantity values for the assessment of measurement uncertainty, called type A evaluation. The conditions under which the measurement is obtained can be: repeatability, intermediate precision, and reproducibility condition. The repeatability condition which is the relevant for this investigation is defined as the “condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time" [6]. The intermediate precision and reproducibility mark more changes in the set of conditions and are understood for more extended time period.

Influence factors introduced in 3.2. are resulting in variations in the repeated observations. The type A evaluation provides an estimate of the sum of these variations with the experimental standard deviation of the mean (Eq. 1).

$$s(\bar{q}) = \sqrt{\frac{1}{n(n-1)}\sum_{j=1}^{n}(q_j - \bar{q})^2} \qquad (1)$$

Where $\bar{q}$ is the arithmetic mean of *n* independent repeated observations.

3. Performance evaluation under quasi-static condition

The measurement uncertainty is tightly associated with the multi-axis repeatability performance of the machine tool. Thus a top-down approach, starting from the variation of the repeated measurements needs to be followed during the evaluation of the sources. The target condition is the effect of different levels and directions of the applied loads on the repeatability performance of the system.

3.1. Definition of indictors

Repeatability of measurements obtains the agreement between repeated measurements under repeatability condition. During geometric tests the determination of repeatability excludes the positioning repeatability of linear axis since the measurements are taken only after the machine movement has stopped. ISO 230-2 [9] concludes that in case of unloaded measurements the uncertainty estimation of the repeatability only defined by the environmental variation. ISO 230-4 [8] is applicable for circular tests for numerically controlled machine tools, but as other international standards, do not deal with repeated circular measurements either.

Two ways of indicating repeatability performance will be investigated in this paper for quasi-static loaded characterisation. The first way is the "largest gap" repeatability (Eq. 2 and 3). In this case according to [10], the uni-directional repeatability is defined as the largest gap between two CW (clockwise) or CCW (counter-clockwise) traces in the measurement plane obtained by two measurement made within a short interval of time. Bi-directional repeatability which is defined as the largest gap between a CW trace and a CCW trace in the plane of the measurements.

$$r_{CW} = max.\,[\mathrm{max.}\left[q_{CW_j}(\theta_i)\right] - min.\left[q_{CW_j}(\theta_i)\right]] \qquad (2)$$

$$r_{CCW} = max.\,[\max.\left[q_{CCW_j}(\theta_i)\right] - min.\left[q_{CCW_j}(\theta_i)\right]] \tag{3}$$

$$r_B = max.\,[\max.\left[q_{CW_j}(\theta_i); q_{CCW_j}(\theta_i)\right] - min.\left[q_{CW_j}(\theta_i); q_{CCW_j}(\theta_i)\right]] \tag{4}$$

In the equations *j=1, 2, ..., n and i=1, 2, ..., m,* where n is the number of repetitions and m is the number of the readings in one circle, $q_{CW_j}(\theta_i)$ and $q_{CCW_j}(\theta_i)$ marks the corresponding reading for the given rotating angle (θ). It has to be noted that the velocity of the feed rate motion can change during the circular motion which will effect an error in θ_i. The contribution of this error was investigated and found to be negligible.

The second expression is defined through the type A uncertainty (Eq. 5-7), as the average value of the experimental standard deviations of the means for each reading angle $s(\bar{q})$.

$$R_{CW} = \frac{\sum_{i=1}^{m}\sqrt{\frac{1}{n(n-1)}\sum_{j=1}^{n}(q_{CW_{i,j}} - \bar{q})^2}}{n} \tag{5}$$

$$R_{CCW} = \frac{\sum_{i=1}^{m}\sqrt{\frac{1}{n(n-1)}\sum_{j=1}^{n}(q_{CCW_{i,j}} - \bar{q})^2}}{n} \tag{6}$$

$$R_B = \frac{\sum_{i=1}^{m}\sqrt{\frac{1}{n(n-1)}\sum_{j=1}^{n}(q_{i,j} - \bar{q})^2}}{n} \tag{7}$$

These statistical indicators are used in order to have a representative single value information which can be used for deriving conclusion on the uncertainty and the repeatability of the measurement along the circular trajectory under different measurement conditions.

3.2. Test setup - inhomogenities in the repeatability condition

According to the repeatability conditions the performance of a multi-axis system can be effected through non-systematic parameters such as: backlash, hysteresis, contouring error of each axis, play in the spindle, stick slip motion errors, certain thermal errors, vibrations from the servo drives, interpolation errors and servo errors. As it will be demonstrated the effects of these sources are varying depending on certain parameters in the workspace. The test setup which can be seen on Figure 2 was designed to enhance the describtion of the inhomogenities connected to the repeatability. The most important inhomogenities which are considered, includes the effect of the (1) magnitude, (2) the direction and the (3) position of the applied quasi-static force.

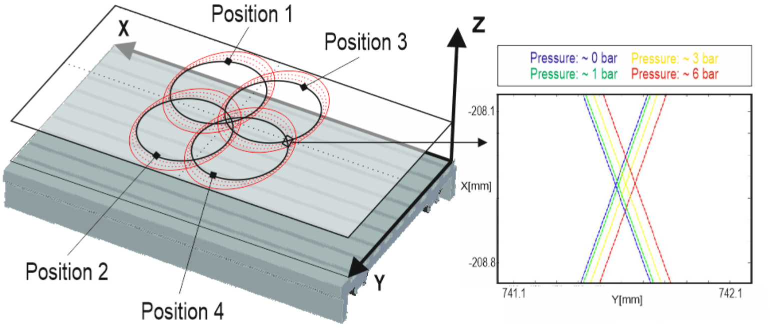

Figure 2: The measurement setup for a three-axis machine tool

The proposed test setup for the investigation of the repeatability performance of a three axis milling machine contains measurement at four different positions around the middle of the table, 4 different load levels, clockwise and anti-clocwise senses of contouring,. The effect of the feed rate during contouring was not an investigated parameter, it was selected to be low (500 mm/min).

3.2. Results and discussion

After the experimental observations a data analysis was applied to calculate the measurement results. In addition also to ensure that the measurements are not significantly affected by the uncertainty in the level of the applied force or the setup stability.

The determined indicators for the measurement uncertainty and repeatability are in Table 1. The largest gap indicators (r_{CW}, r_{CCW}, r_B) are representing the “worst case” of the repeatability, while R_{CW}, R_{CCW} and R_B are affected by all the repetitions, representing more the whole sample. According to ISO 230-9 [11] the maximum value of the estimated standard deviation is the base for calculating the standard uncertainty, while GUM uses the standard deviation of the mean of the repetitions. As another indicator the maximum value of this latter was used.

Table 1. Indicators for the measurement uncertainty and repeatability

	28.45 N (unloaded)				111.16 N				363.16 N				740.65 N			
[µm]	**Pos. 1**	**Pos. 2**	**Pos. 3**	**Pos. 4**	**Pos. 1**	**Pos. 2**	**Pos. 3**	**Pos. 4**	**Pos. 1**	**Pos. 2**	**Pos. 3**	**Pos. 4**	**Pos. 1**	**Pos. 2**	**Pos. 3**	**Pos. 4**
r_{CW}	5.73	3.14	1.51	2.73	1.07	2.31	1.46	2.25	1.70	1.66	1.02	1.83	1.63	1.05	0.82	1.45
r_{CCW}	2.14	2.71	1.74	1.73	1.36	2.16	0.94	2.24	1.60	1.89	0.87	1.33	1.40	1.15	0.63	1.07
r_B	9.44	6.39	6.63	6.86	5.53	5.84	5.11	7.44	7.10	8.32	7.47	9.43	8.14	9.57	7.96	10.81
R_{CW}	1.49	1.45	0.64	1.38	0.53	1.18	0.62	1.33	0.97	0.77	0.41	0.77	0.87	0.35	0.28	0.73
R_{CCW}	0.72	1.18	0.61	0.91	0.68	1.25	0.54	0.94	0.97	0.87	0.39	0.8	0.70	0.70	0.23	0.61
R_B	1.11	1.31	0.62	1.15	0.60	1.21	0.58	1.14	0.97	0.82	0.4	0.79	0.78	0.53	0.26	0.67
Estimated standard deviation (max. value)	3.20	1.59	0.88	1.42	0.69	1.20	0.73	1.22	0.92	1.02	0.51	1.02	0.83	0.66	0.41	0.73
Max. value of the standard uncertainty (k=3)	5.54	2.75	1.53	2.46	1.20	2.08	1.26	2.12	1.59	1.77	0.89	1.76	1.44	1.15	0.71	1.26

The big majority of the indicators are following a clear tendency that maximum deviations and the variability of the repeated measurements are decreasing with the applied higher load. Figure 3 highlights the tendency related to the increase of the applied load by showing the mean values of the indicators from different positions. Only the bi-directional repeatability (r_B) values do not show this behaviour. As this indicator is the largest gap between a CW and a CCW traces, it is sensitive for the hysteresis in the system and also can be used to indicate its value. Uni-directional indicators, r_{CW} and r_{CCW} are sensitive to the backlash and the play (unloaded case) in the system, but even in their case the tendency is clear.

It is obvious that the Type A measurement uncertainty (according to ISO or GUM) is also decreasing. With respect to the test uncertainty contributors, the source of the change in R_{CW}, R_{CCW} and R_B indicators on different load levels is the change of the repeatability of the machine tool, since the rest of the parameters should not affect the change in the level of the applied load. However the quantification of this change has a dependency on the experimental setup (after Table 1) as the repeatability is inhomogeneous in the workspace.

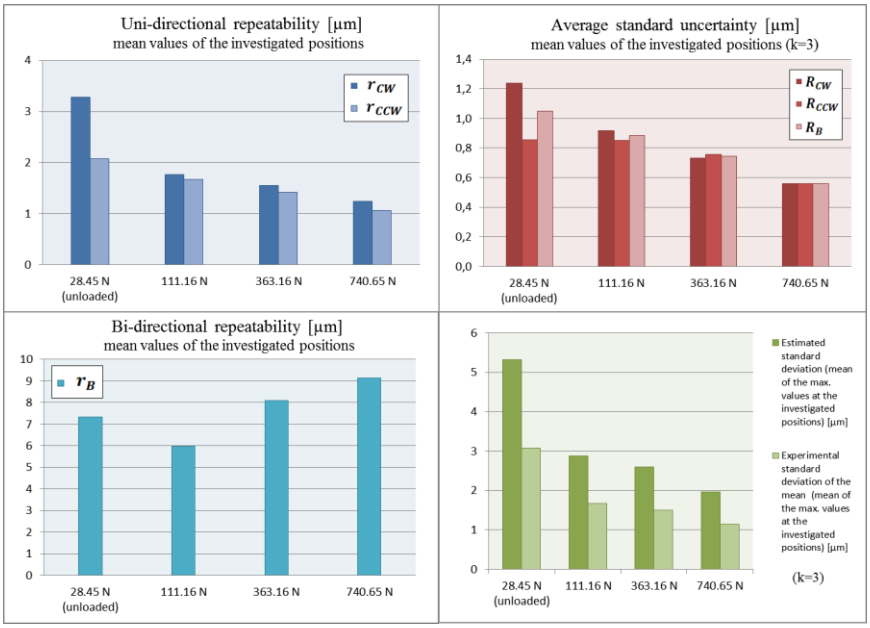

Figure 3: Mean values of the defined indicators

In case of a multi-axis system it is possible that the repeatability of each axis is different, furthermore certain contributors for instance the play in the spindle can be sensitive to the direction of the applied load as well. So the final repeatability is dependent on the involvement of the axes and the response of all the random sources for the direction of the load. Figure 4 shows how these differences can be indicated with circular measurements on different load levels. It is hard to see clear conclusion in the unloaded case with the big variability of the measurements, however after increasing the load with the exclusion of play from the system, the significant differences between X (0°, 180°, 360°) and Y direction (90°, 270°) is more obvious.

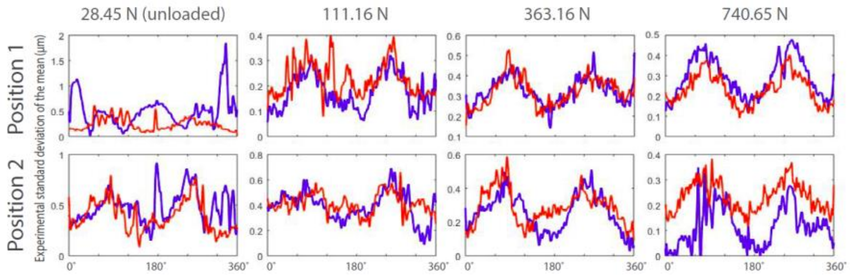

Figure 4: Experimental standard deviation of the mean of the repeated measurements around the circular path (~28350 readings)

4. Conclusions

According to the experiments the repeatability of the system can be in the magnitude of the errors. The sources of the repeatability of a machine tool are random errors, which cannot be compensated, just corrected with expensive intervention. Also the judgment of the quality of the measurement can be misleading, since in many cases the instrument or the setup itself is seen as the biggest contributor to the measurement uncertainty. However in case of machine tool testing as it can be seen on the indicators the machine tool itself can be the biggest contributor.

The quasi-static response of the machine tool for a higher load result a higher systematic deviation (uncut material) on the workpiece, meanwhile as it was introduced in this paper the random sources affecting the repeatability of the system are reduced. So practically in the machine tool performance point of view the accuracy of the machine tool is reduced, while the precision is increased. The identification of these opposing effects is important because the systematic deviation (uncut material) can be compensated (as it was demonstrated in [12]) meaning that with a higher load level higher part quality can be reached. Furthermore in case of finishing conditions the role of repeatability is more serious and can result serious capability variation. It was presented that repeatability is inhomogeneous gor different directions as well, which information after the characterisation can be used to identify sensitive directions.

According to GUM, the measurement uncertainty was reduced by more then 60% through the increased repeatability of the system with the higher load levels during testing. As a conclusion it can be stated, that one can gain twice from a stiff and repeatable machine tool. On one hand for the same level of load the accuracy is not reduced as much, and on the other hand the precision is enhanced, while the test uncertainty can be reduced.

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