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Utilization of machine tool repeatability in kinematic modelling

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Abstract

Modelling of non-systematic variations in the positioning performance of machine tools can support the understanding of capability variation in manufacturing processes. Kinematic characterisation is implemented through repeated measurements, which include variations connected to the performance of the machine tool. This paper addresses the integration of the positional repeatability to kinematic modelling through the utilization of direct measurement results. The statistical population of random errors along the single-axis travel first requires the proper management of experimental data. In this paper a methodology is presented for the determination of repeatability under static and unloaded conditions as an inhomogeneous parameter in the workspace. In a case study the component errors of a linear axis were investigated with repeated laser interferometer measurements to quantify the estimated repeatability and express it in the composed repeatability budget. The conclusions of the proposed methodology outline the sensitivity of kinematic models relying on measurement data, as the repeatability of the system can be in the same magnitude as systematic errors.

Machine tool repeatability, Uncertainty estimation, Kinematic modelling

1. Introduction

Machine tool repeatability is one of the root causes of capability variation in the manufacturing process. A sufficient quantitative description of these variations according to different conditions leads to a better characterisation of machine tool performance and yields higher controllability for the process. The field of kinematic modelling in manufacturing science is dominated by the characterization of reproducible systematic errors as they can be the object of compensation. As will be demonstrated, the repeatability can be in the magnitude of the systematic errors, thus relying only on systematic error sources and including only their effect in the error budget can be misleading.

This paper presents an interpretation of direct measurement results that facilitates the integration of machine tool repeatability in kinematic modelling on the volumetric error level. The interpretation consists of I) the clarification of the conditions in which the repeatability is understood, II) the consideration of relevant inhomogeneities causing the variation of repeatability, III) the statistical management of experimental data, IV) the definition of new parameters and their comparison with existing standardised indicators in the repeatability budget for a single axis. In a case study the component errors of a three axis machine tool were investigated with repeated laser interferometer measurements.

2. Estimator for machine tool repeatability

Estimation of repeatability in this work follows the quasi-static and unloaded conditions defined in ISO 230-1 [1]. According to ISO, the repeatability of axis positioning is defined through the standard deviation of the positioning deviation values obtained by a series of repeated approaches to a given axis position [2][3].

According to the repeatability conditions the performance of a multi-axis system can be affected by play in components, assembly, backlash, hysteresis (due to inertia forces), contouring error of each axis (including interpolation errors) and stick-slip motion errors. These effects are not evenly distributed along a single axis travel range or, in case of multi-axis positioning, workplain or volume, resulting in inhomogeneities in the machine tool performance. The most significant factors, which can influence the estimation of repeatability, include the uncertainty of the measurement instrument and thermal deformations during testing or external environmental changes. Regarding the effects of these root causes on the repeatability of the system, the distribution of the experimental frequency needs to be properly analysed in order to separate random and systematic variations of the calculated standard deviations. Therefore it is not straightforward that the repeatability as standard deviations of the measurements can be directly utilized in kinematic modelling since it is spatial dependent in the measurement travel range.

3. Methodology: Statistical management of experimental data

ISO 230-9 [4] gives internationally accepted guidance for the measurement uncertainty assessment of the estimator of standard deviation, representing the repeatability of the positioning performance of machine tools. All systematic variations along the axis travel range are considered as an attribute for the mean value of the repeated measurements. And, most importantly, it is assumed that “the measurement uncertainty for individual measurements does not change” [4]. According to the above mentioned inhomogenities, indication of random and systematic variation in the repeatability along the whole or one particular part of the measurement travel can highlight valuable information for a more accurate kinematic modelling.

The most important steps of the proposed iterative statistical assessment for the separation of random and systematic variations (and measurement accidents) can be seen in Figure 1. The raw input data is the repeated direct measurement according to ISO 230-1 [1]. The assessment is iterative since any modification in the dataset will affect the outcome of the regression.

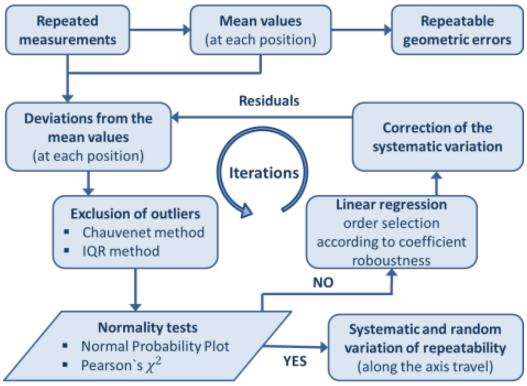

Figure 1. The operational chart of the statistical management of the experimental data

An example of the normality test results can be seen in Figure 2. As noted in [5], as the machine will later make a workpiece just once, the standard deviation in a single measurement should be derived from the measurement dispersion, and not the ‘standard deviation of the mean’, which is the GUM [6] practice to express the standard uncertainty.

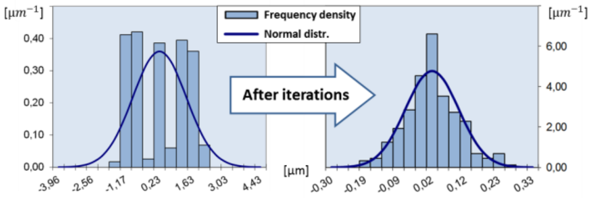

Figure 2. Normality tests before and after the statistical management of the measurement data in case of straightness errors

4. Results and representation of repeatability performance

A case study was implemented for the estimation of the repeatability of a linear axis of a three-axis milling machine. A laser interferometer was used for the repeated direct measurements of component errors of a single axis. Figure 3 shows the quantified random variations of repeatability along the measurement travel at each position in case of a straightness error measurement.

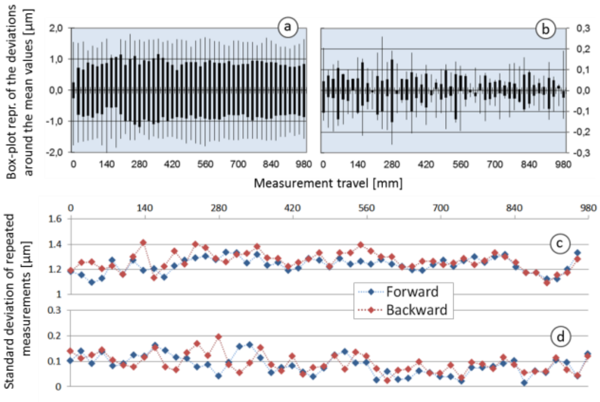

Figure 3. Repeatability along the measurement travel
a-c) before the statistical management and
b-d) the pure random variation - normality criteria is satisfied

4.1 Repeatability budget

The repeatability budget in Table 1 contains the maximum values (worst-case scenario) of the estimated repeatability in case of each component errors. The budget highlights the significant contribution of the separated systematic and random variation of repeatability along the measurement travel.

Table 1 Single value representation of the repeatability performance (maximum value along the measurement travel), k=2

Component error (of X axis)	Unit	After ISO 230-2 [2]	After utilization	Due to pure random var.	Random/ Systematic
Positioning (↑)	µm	3.92	3.44	0.75	28%
Positioning (↓)	µm	3.85	3.08	0.69	29%
Bidirectional Positioning	µm	6.28	5.66		
Angular Yaw (↑)	µm/m	10.16	9.8	2.42	33%
Angular Yaw (↓)	µm/m	8.84	8.84	2.65	43%
Bidirectional Yaw	µm/m	12.48	12.3		
Angular Pitch (↑)	µm/m	11.54	10.52	1.69	19%
Angular Pitch (↓)	µm/m	10.86	10.16	1.87	23%
Bidirectional Pitch	µm/m	21.48	20.62		
Straightness in Y direction (↑)	µm	3.45	2.16	0.91	73%
Straightness in Y direction (↓)	µm	2.24	2.08	0.93	82%
Bidirectional Straightn. in Y dir.	µm	4.10	3.38		
Straightness in Z direction (↑)	µm	5.34	5.2	0.66	14%
Straightness in Z direction (↓)	µm	5.64	5.28	0.78	17%
Bidirectional Straightn. in Z dir.	µm	9.73	9.48		

5. Conclusions and future work

The proposed methodology enables quantification of the repeatability inhomogeneities along the measurement range of linear axis. This supports advanced measurement data utilization for kinematic modelling. The proposed statistical management approach facilitates the proper handling of experimental data to represent systematic and random variations of repeatability, thus enabling the determination of position dependent repeatability performance. As was demonstrated in the repeatability budget (Table 1), the random variation of the repeatability along the axis travel range can be significant. This highlights that the “worst case” characterisation, through the maximum standard deviation of the measurements can be insufficient and can be far from normality criteria. Furthermore the determined repeatability performance of the investigated machine tool can be in the magnitude of the measured geometric errors (for instance positioning: 6-26 µm, straightness: 2-35 µm).

The proposed methodology is the first step to drawing conclusions on volumetric error level on the repeatability of multi-axis performance. The following step is to compose a computational framework for the modelling of the effect of repeatability in kinematic behaviour. This requires the mapping of the dispersion due to the repeatability at the estimated positions from each axis to the work volume for the prediction of machine tool errors from probabilistic point of view.

References

[1] ISO 230-1:2012, "Test code for machine tools - Part 1: Geometric accuracy of machines operation under no-load or finishing conditions”

[2] ISO 230-2:2006, "Test code for machine tools - Part 2: Determination of accuracy and repeatability of positioning numerically controlled axes”

[3] ISO 10791-4:1998, "Test conditions for machining centres - Part 4: Accuracy and repeatability of positioning of linear and rotary axes.”

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[5] Schwenke H et al. 2008, Geometric error measurement and compensation of machines - An update, *CIRP Annals - Manufacturing Technology*, **57**, 110–125

[6] ISO/IEC Guide 98-3:2008, "Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)”