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The role of measurement and modelling of machine tools in improving product quality

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Abstract. Manufacturing of high-quality components and assemblies is clearly recognised by industrialised nations as an important means of wealth generation. A "right first time" paradigm to producing finished components is the desirable goal to maximise economic benefits and reduce environmental impact. Such an ambition is only achievable through an accurate model of the machinery used to shape the finished article. In the first analysis, computer aided design (CAD) and computer aided manufacturing (CAM) can be used to produce an instruction list of three-dimensional coordinates and intervening tool paths to translate the intent of a design engineer into an unambiguous set of commands for a manufacturing machine. However, in order for the resultant manufacturing program to produce the desired output within the specified tolerance, the model of the machine has to be sufficiently accurate. In this paper, the spatial and temporal sources of error and various contemporary means of modelling are discussed. Limitations and assumptions in the models are highlighted and an estimate of their impact is made. Measurement of machine tools plays a vital role in establishing the accuracy of a particular machine and calibrating its unique model, but is an often misunderstood and misapplied discipline. Typically, the individual errors of the machine will be quantified at a given moment in time, but without sufficient consideration either for the uncertainty of individual measurements or a full appreciation of the complex interaction between each independently measured error. This paper draws on the concept of a "conformance zone", as specified in the ISO 230:1 – 2012, to emphasise the need for a fuller understanding of the complex uncertainty of measurement model for a machine tool. Work towards closing the gap in this understanding is described and limitations are noted.

Keywords: Computer aided design; computer aided manufacturing; uncertainty; errors; machine tool modelling; machine tool measurement

1 Introduction

Manufacturing has developed rapidly since the days of artisans producing quality products and skilled machine operators modifying cutting parameters, offsets, depth of cut, etc. based upon experience and as a direct response to the behaviour of the machine. Production in high-value manufacturing (HVM) is ever more reliant on computer numerically controlled (CNC) machine tools producing parts designed and programmed using computer aided design (CAD) and converted into a language understood by the CNC using computer aided manufacturing (CAM) software. This conversion from design intent of the component in CAD into a CNC-understandable part program to describe the movement of the feed axes requires a post-processor that describes the machine on which the part is to be manufactured. Such machine models are, however, normally idealised representation of axis limits and orientations, rather than a true description of the production machine. The machine subsystems are manufactured and assembled within tolerances and are subject to wear over time. Therefore, better models are required to describe the actual machine, and these must be updated over time because the model only remains accurate for as long as the most recent measurement data truly represents the machine.

Figure 1 presents a schematic of the process in which the deterministic parameters are the design intent, idealised machine model and drive parameters. For a standard CAD/CAM system, the "unmodelled effects" block captures the influences on accuracy that are not normally considered, but which are critical in HVM. This paper discusses the elements of the machine that require modelling to complete the machine description and the issues of measurement that can have a negative influence on the final accuracy of the model.

2 Machine tool modelling

In its most basic form, the definitions of axes of motion and configurations of machines are described by both international standards [1,2] and research literature [3,4] to promote a common terminology and classification for the idealised model.

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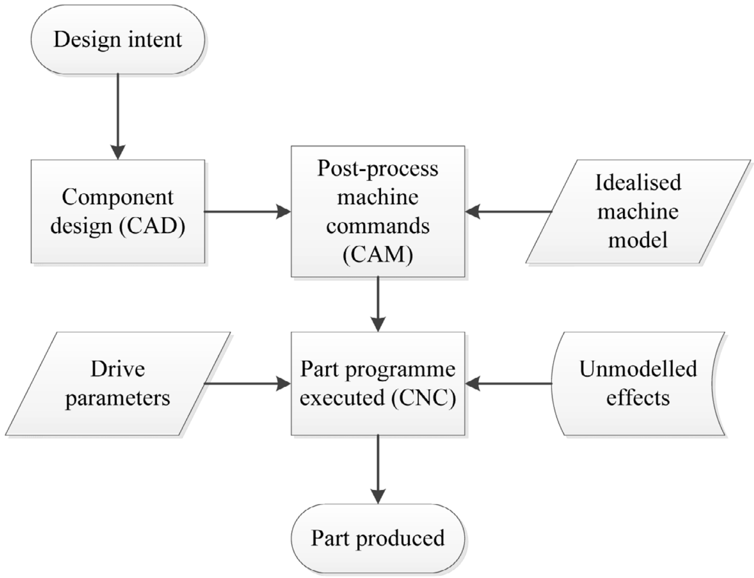


Fig. 1. Flow of CAD/CAM from design to production.

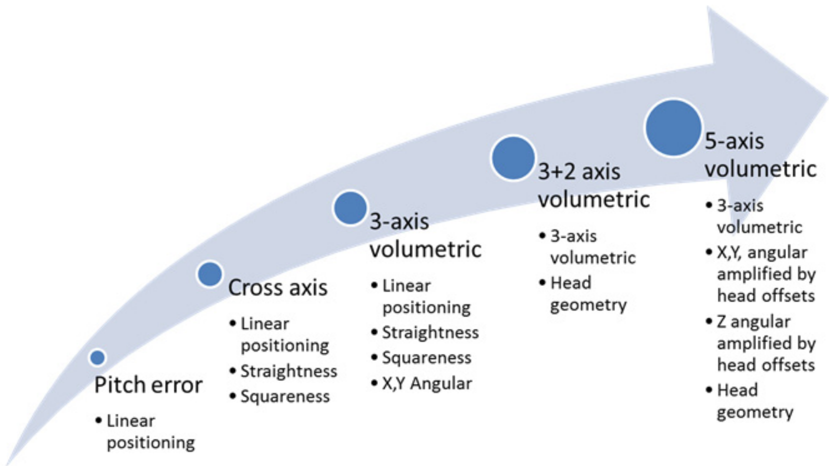


Fig. 2. Different modelling approaches for geometric accuracy.

2.1 Pseudo-static geometric errors

There are well-established models for the pseudo-static errors in Cartesian axis machine tools [5,6] that consider the six freedoms of motion for each linear axis and the non-orthogonality that result from inherent errors in the manufacturing and build processes of the machine itself. They are generally based on a kinematic model of the machine structure and homogenous transformation matrices. These basic models can be used to alter the part program [7], can be included in the post-processor to adjust machine trajectory [8] or be implemented as a compensatory algorithm in an external compensation system [9] or within the CNC itself [10].

Although alternative notations are used, the terminology for these errors defined by the international standards organisation [11] includes:

– Translational errors defined as E_{mn}, where an error in the m-axis direction is caused by motion of the n-axis. For example E_{XX} is a linear positioning error, while E_{XY} is a straightness of the Y-axis in the X-axis direction.
– Rotational errors defined as E_{kn}, where an error of rotation about the k-axis is experienced as the n-axis is moved. k is defined as A, B, C for rotation about the X, Y and Z-axes, respectively. For example E_{AX} is rotation of the X-axis about the X-axis (roll) and E_{BZ} is rotation of the Z-axis about the Y-axis.

Although standards provide methods for, and tolerances of, individual error sources on a machine tool, there is at present no agreed single-valued performance for the machine. Figure 2 shows different methods of computing the combined accuracy of all the geometric errors. Perhaps surprisingly, many machine tool builders still employ the simplest model where only the linear errors are considered.

As highlighted in [12], the methods by which the errors are modelled can be a compromise between exactness, requisite computing power and available measurement

Table 1. Comparison of head error calculation methods.

Method	Calculated error (microns)
Root mean square of error contributors	34
Maximum vector	81
Maximum difference between vectors	150

technology. One approach to evaluating the errors from rotary axes is to calculate the root mean square (RMS) of the errors of the rotary axes and to add this value to the errors from the Cartesian axes. This is considered the "3 + 2" model in Figure 2.

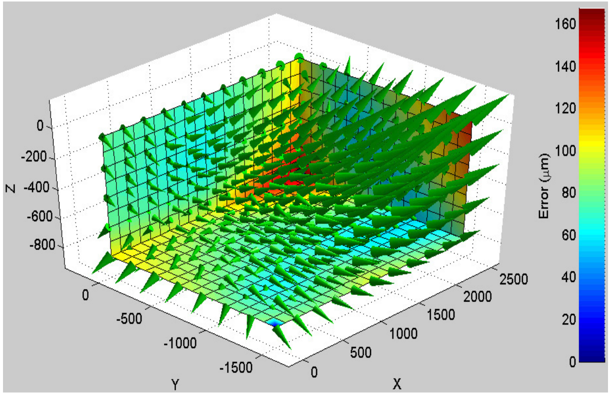
Considering only the RMS is insufficient to represent truly the capability of the head as a contributor to the total machine errors. A fuller analysis requires that all the error vectors are calculated and the largest difference between any two vectors represents the capability of the machine. Table 1 shows the different values obtained by processing measured data from a milling machine in the three different ways listed and highlights the dramatic underestimation of the simplified model.

Computation of the full 5-axis volumetric performance requires a similar treatment for all errors on the machine – the model must consider the effect and amplification of all error sources in all axis positions and generate a set of difference vectors that are then evaluated against each other [13]. Figure 3a shows a vector map for the 5-axis gantry machine analysed in Section 2.2 below. For visualisation, at each 3D position the largest effect of the additional rotary axes is added to the Cartesian total. As the density of the map and number of axes increases, the number of difference vectors increases exponentially. Visualisation of these errors is a non-trivial task; Figure 3b shows 2.7×10^7 comparisons and the largest difference highlighted by an asterisk.

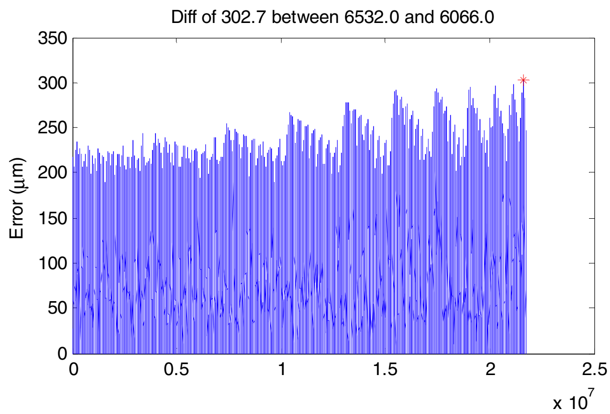
2.2 Effect of build-up of tolerances

Tolerances are usually placed upon each of the individual error sources when specifying a machine for purchase, conducting maintenance or applying compensation. The limits are often placed in accordance with recommendations from ISO standards [21,22]. Table 2 provides an analysis of the 3D spatial errors of a machine shown in Figure 4, considering both 3-axis and 5-axis configurations, and for contrast also presents the case if each error were at its maximum tolerance and with a mean distribution of the errors.

The values in Table 2 can be quite large, but this indicates the worst case vector and usually manifests between locations at the extremities of the working volume. The model data can also be used to generate a histogram as shown in Figure 5, which shows that the typical volumetric errors are between 50 and 70 μm. The distribution is generally Gaussian with extended tail therefore in this case we have a 95% confidence that errors will be within 150 μm.



(a)



(b)

Fig. 3. (a) Error vectors and (b) vector differences in machine working volume.

Table 2. Analysis of accuracy of a gantry machine tool in accordance with ISO tolerance.

Simulation type	Volumetric performance (μm)
ISO standard tolerances	262
Varied tolerances and uncertainties	231
5-axis (Universal head) using standard tolerances	439
5-axis with varied tolerances and uncertainties	303

2.3 Non-rigid body errors

Although machine tools are generally designed to be stiff, in any machine structure there remains an element of compliance in both the individual elements and assemblies. The magnitude of this effect will depend upon the intended use of the machine. For example, where high acceleration and feedrate is demanded then material is removed from the machine structure to reduce inertia. However, even machines that are nominally stiff have to reach

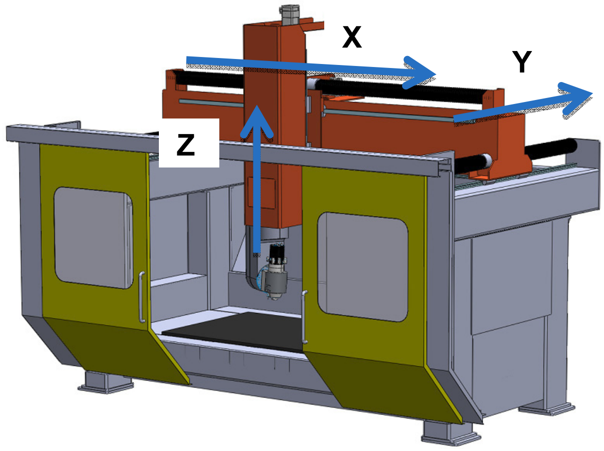


Fig. 4. General overview of the gantry machine used in this case study.

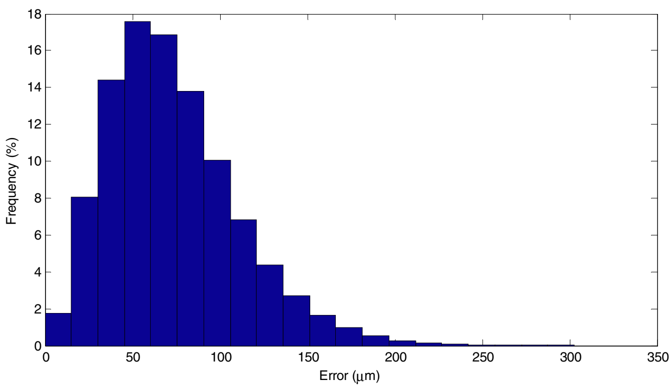
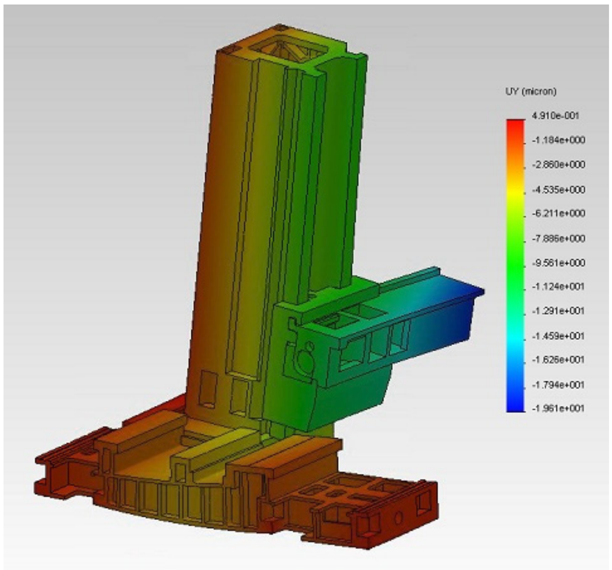
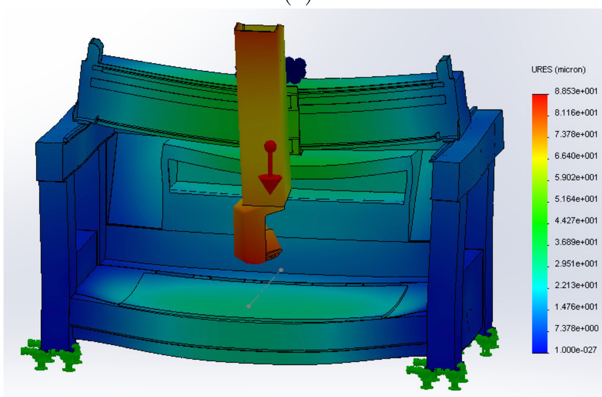


Fig. 5. Hystogram of volumetric accuracy throughout working volume.



(a)



(b)

Fig. 6. FEA simulation of the response of (a) a boring and (b) a milling machine to different positions of the axes.

a compromise at the design stage between the target stiffness and adding material to the structure which increases cost and reduces axis responsiveness.

Modelling effort has in the past not considered the non-rigid case in the same depth as some other machine tool errors [14]. The main reason for this is that it is perceived as being of relatively small significance when compared to geometric and thermal errors, particular on small or ultra-precision machine tools. However, these errors can become significant on medium to large machines with configurations that incorporate cantilever structures or moving tables with large carrying capacity.

Repeating FEA simulations in different locations can predict the non-rigid effect of the machine due to change in loading from the linear and rotary axis positions (Fig. 6). For the example of the case study machine, Figure 6b, a 24 μm/m difference in the E_{YX} error exists between the central position and the extreme of X-axis travel due to bending of the beam.

This "finite stiffness" error can manifest itself as a self-induced distortion due to moving mass, or as a response to the load of a moving workpiece, which can change during operation when material is removed during machining. Modelling of the non-rigid effects is normally achieved by finite element analysis (FEA), where an accurate design model is essential to be able to predict the results [15]. An additional consideration must be made for the effect of cutting force, which can be modelled in FEA as a static force acting between the tool and workpiece.

2.4 Thermal errors

A usual estimate of the thermal effect is a linear multiplier of the temperature by the coefficient of thermal expansion of either the dominant or the scale material. However, this model is far too simplistic.

Figure 7 shows the result of an axis heating test on a linear axis with scale feedback. Each of the coloured lines represents the change over time at a linear target on the axis under study. An initial position error of 10 μm increases with environmental temperature to 18 μm. The graph also shows a position independent drift of up to 10 μm resulting from the internal heat affecting the thermal datum of the scale. Estimating the error requires

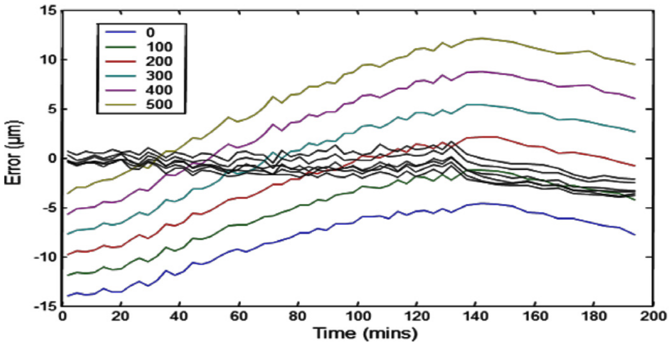


Fig. 7. Feed axis position dependent and position independent thermal error.

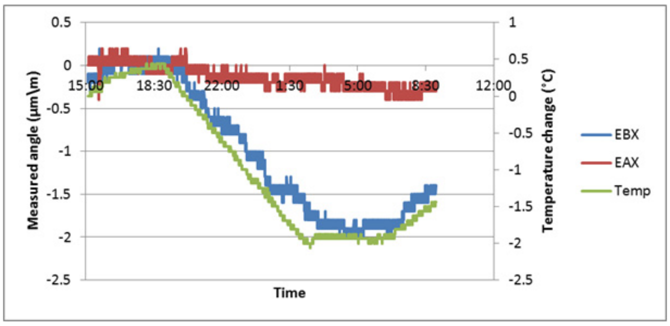


Fig. 8. Effect of temperature on E_{AX} and E_{BX}.

suitable temperature information on the structure, the scale and the axis positions. The cluster of black traces shows the error after compensation using such a parametric model. Bending of support structures such as the column of a C-frame machine also cause position dependent error due to the column bending model which requires a differential temperature measurement from the front to the back of the column and the Z-axis position.

An example error induced by environmental temperature fluctuations is shown in Figure 8, where the E_{YX} of a C-type machine tool changes by around 20 μm/m for approximately a ± 1 °C ambient temperature change. Such an error will affect machining, but will also, depending upon the instant of measurement, affect the expected or calibrated performance of the machine.

Modelling of thermal errors is the subject of significant amounts of research to address both the machine and the effects of the process. Parametric [16], FEA [17] and "black box" [18,19] approaches are often used to solve various problems. To obtain robust levels of accuracy in the models, significant effort can be required which in the case of black box models is in training, while for FEA it is in the determination of a variety of boundary conditions.

In this paper, we shall only make the statement that modelling of machine response is essential for reproducible machine performance and that temperature effects during measurement must be carefully analysed and included within the uncertainty budget.

2.5 Dynamic errors

Other errors of the machine, and additional complexity, arise from the dynamic nature of the machining process. The CNC is subject to contouring errors, gain and scale mismatch, vibration and other dynamic effects. The dynamics of the machine tool can be broadly split into deviation from the rigid-body geometric assumption and the interpolation effects in translating the command movement into a path profile.

Each of the pseudo-static geometric errors can be modified by inertial forces due to shifting load, acceleration, poor support, etc. Consideration of these errors is outside the scope of this paper, but it is worth noting that when measuring machines to calibrate static models, any dynamic data must be treated with caution and differences between the static and dynamic state of the machine must be noted.

3 Machine tool measurement

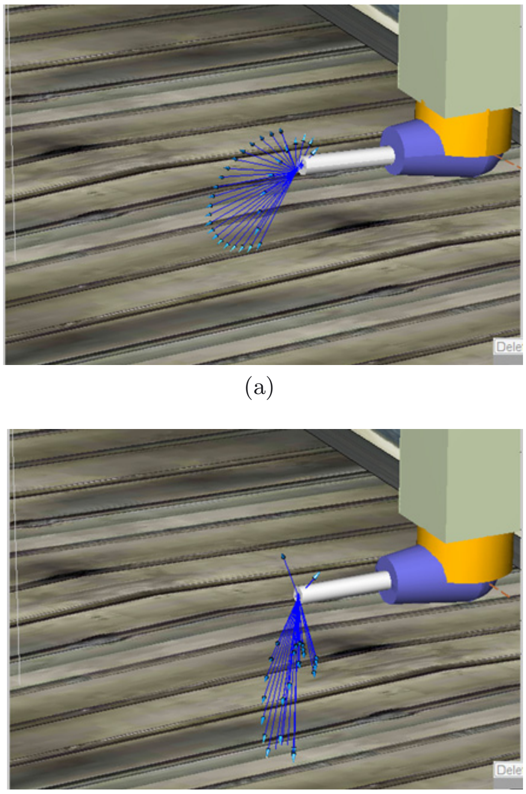
The previous sections have described the importance of comprehensive modelling of machine tools. Calibrating the parameters of the model by measurement is equally important. It is essential that the data is captured with minimum uncertainty of measurement and due consideration for cross-talk between errors, to ensure that the model is as close to the real machine and processes as possible.

A particular crossover between modelling the machine and measurement is where the errors from one part of the machine can influence the measurement of another. For example, self-centering probes or 'chase the ball' methods [20] provide indicative information from a multi-axis measurement. A commercial system call the R-Test system from IBS can be used to obtain values for axis squareness, non-concentricity, etc. However, this rich source of measurement information can be more fully exploited by generating new strategies that use the linear axes to move around the fixed pivot. However, the linear axes used to maintain alignment during such measurement are in themselves subject to geometric, non-rigid and thermal deformations. Figure 9 shows the error vectors when moving around a fixed point. Figure 9a shows the results if the Cartesian axes were error-free, while Figure 9b shows a completely different result due to the errors in the linear axes.

Routines must be devised to decouple individual errors and isolate the rotary axis error sources. This may sometimes be possible using either reversal techniques or by direct compensation of the values by pre-measurement of the contaminating axes. Figure 10 shows the R-Test output from a 'tool centre-point' routine involving 180 degree rotation of both B- and C-axes.

Decoupling the offset between the B and C-axes is achieved simply by reversal of both rotary axes (1) assuming no thermal change between tests which is realistic since the test can be performed within minutes.

$$E_{B0C} = (X_{B90,C0} - X_{B-90,C180})/2. \tag{1}$$



(a)

(b)

Fig. 9. Measurement of rotary axis error (a) with no Cartesian errors and (b) with Cartesian errors.

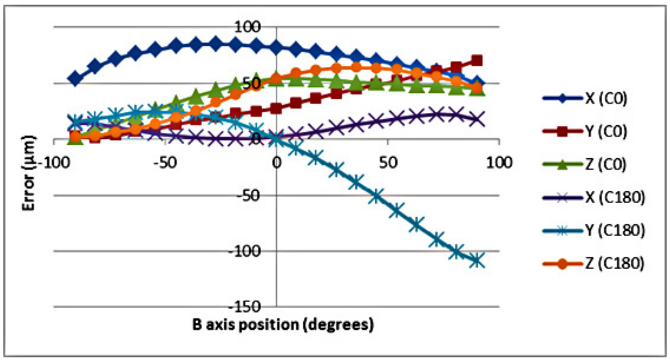


Fig. 10. Example output from RTest system.

The squareness of the B-axis to the C-axis in the YZ plane can be completely decoupled using similar moves:

$$E_1 = \left(Y_{B90,C0} + Y_{B-90,C0}\right)/2 - Y_{B0,C0} \quad (2)$$

$$E_2 = \left(Y_{B90,C180} + Y_{B-90,C180}\right)/2 - Y_{B0,C180}. \quad (3)$$

The final error is determined by (4):

$$E_{B0A} = (E_2 - E_1)/2. \quad (4)$$

This error is traditionally determined from equation (1) by comparing the position of the tool against a reference face but includes additional uncertainty from the alignment of the face with the measuring plane and the flatness of the face. Other errors can only be partially decoupled given knowledge of the contamination. For example the offset between the spindle and the B-axis (E_{Y0B}) can be decoupled from the Cartesian axes but is influenced by B positioning (E_{BB}).

3.1 Effect of the uncertainty of measurement

The conformance zone [23, 24], is that part of the design tolerance that remains after the uncertainty of measurement has been considered. Conversely, this concept also means that it is possible for an error component to be measured within tolerance, when in fact it exceeds the required performance. When considering tolerances applied to machine accuracy, a calibration can provide useful information with due consideration for the measurement uncertainty. This assessment provides a picture of the conformance zone that is only valid for that moment in time, which for CMMs and machines in a temperature controlled environment may be sufficiently representative for the duration between calibrations, but this is often not the case for typical machine tools. Various factors can contribute to the uncertainty during production including unknown thermal and finite stiffness errors in the machine model and other processes such as cutting, hydrostatics and fixturing related errors which contribute to a reduction in the conformance zone as indicated by Figure 11 and conceivably smaller than the tolerances of the part being machined.

Returning to the concept of volumetric analysis from Section 2.2, the combined effects of the tolerance can provide a significant combined uncertainty. Modelling of the overall uncertainty value using Monte Carlo simulation or Bayesian theory [23, 25] can provide a probability of measurement uncertainty. Considering the 3- and 5-axis volumetric performance simulations, uncertainties in the individual errors of $\pm 10\%$ (based on an average relationship between typical errors from a laser interferometer system typically used for machine tool error measurement and the ISO standard tolerances) could contribute up to 53 μm and 88 μm, respectively.

3.2 Improving quality from the simulated performance

Calculating volumetric accuracy and volumetric performance throughout the working volume informs the designer and user of the capability of the machine to produce parts generally or to compare machines. Quality may be improved by moving the component in the volume where error variation is lower. The results can inform refurbishment effort by showing the effect of improvement prior to carrying out such expensive work.

4 Conclusions

Product quality is directly affected by the accuracy of the model of the machine tool that is used to post-process the

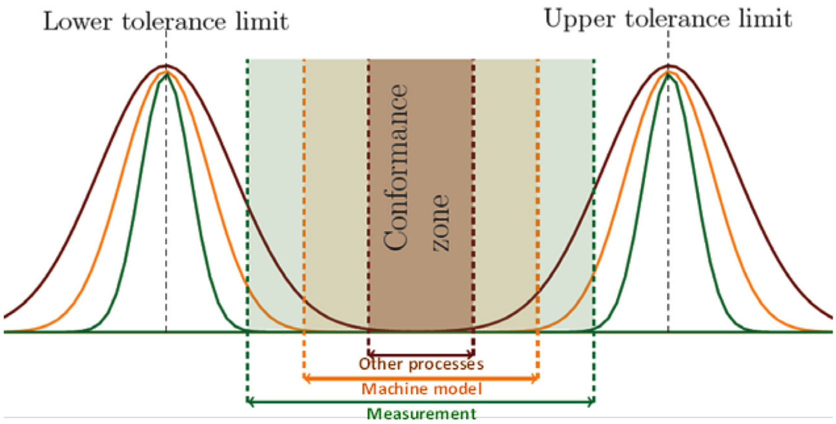


Fig. 11. Diminishing conformance zone with machine uncertainty.

CAD model of a part into a series of commands executed by the CNC of a machine tool. Machine tools require micron level accuracy over a range of dynamic, load and temperature conditions. A range of different modelling techniques are directly applicable to machine tools: Parametric models; Finite Element Analysis; Artificial intelligence.

Although work on machine tool accuracy has been ongoing for many years, there remain a great number of challenges in modelling, measuring and data processing. This paper has presented some of the research work being conducted on enhancing the accuracy of models of machine tools and on ensuring they are calibrated in accordance with the intended specification. Simulations of the measured accuracy of a case-study machine have been compared against the maximum error that could be experienced if all individual tolerances were met. An estimate of the maximum possible effect of uncertainty of measurement has also been presented.

This work will ultimately lead to a better understanding of the capability of machine tools to inform those who are drafting purchase specifications for new machine tool assets. It will also help to bridge the gap in understanding between the desires of design engineers for tighter tolerances and the measured accuracy of manufacturing machines and the unavoidable uncertainties in measurement assumptions within models.

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References

1. ISO 841:2001 Industrial automation systems and integration – Numerical control of machines – Coordinate system and motion nomenclature
2. ISO 16907 Numerical compensation of geometric errors of machine tools
3. H. Schwenke, W. Knapp, H. Haitjema, A. Weckenmann, R. Schmitt, F. Delbressine, Geometric error measurement and compensation of machines – An update, CIRP Ann. Manuf. Technol. **57**, 660–675 (2008)
4. R. Callaghan, *Machine tool and motion error standardized definitions for simplified error modeling*, Tech. Report (Independent Quality Labs, Inc., 2007)
5. D.G. Ford, S.J.R. Postlethwaite, J.P. Allen, M.D. Blake, Compensation algorithms for the real-time correction of time and spatial errors in a vertical machining centre, J. Eng. Manufact. **214**, 221–234 (2000)
6. J.H. Lee, Y. Liu, S.H. Yang, Accuracy improvement of miniaturized machine tool: Geometric error modeling and compensation, Int. J. Mach. Tools Manufact. **46**, 1508–1516 (2005)
7. M.V. Nojedeh, M. Habibi, B. Arezoo, Tool path accuracy enhancement through geometrical error compensation, Int. J. Mach. Tools Manufact. **51**, 471–482 (2011)
8. H. Spaan, Software error compensation of machine tools, thesis, Technical University of Eindhoven, 1995
9. S.R. Postlethwaite, Electronic based accuracy enhancement of CNC machine tools, Ph.D. thesis, 1992
10. A.P. Longstaff, S. Fletcher, A. Myers, D.G. Ford, Volumetric compensation of machine tools makes geometric errors negligible, in *3rd Int. Congress on Precision Machining, 2005*, Vol. 3, pp. 209–216
11. ISO 230-1, 2012. Part 1: Geometric accuracy of machines operating under no-load or quasi-static conditions
12. A.P. Longstaff, S. Fletcher, A. Poxton, A. Myers, Comparison of Volumetric Analysis Methods for Machine Tools with Rotary Axes, LAMDAMAP 2009 (Euspen Ltd, 2009), pp. 87–96
13. S. Fletcher, A.P. Longstaff, A. Myers, Defining and Computing Machine Tool Accuracy, LAMDAMAP 2009 (Euspen Ltd, 2009), pp. 77–86
14. S.-M. Wang, H.-J. Yu, H.-W. Liao, A new high-efficiency error compensation system for CNC multi-axis machine tools, Int. J. Adv. Manufact. Technol. **28**, 518–526 (2006)
15. D.T. Huang, J.J. Lee, On obtaining machine tool stiffness by CAE techniques, Int. J. Mach. Tools Manufact. **41**, 1149–1163 (2001)

16. S. Fletcher, A.P. Longstaff, A. Myers, Flexible modelling and compensation of machine tool thermal errors, in *20th Annual Meeting of American Society for Precision Engineering, 2005*
17. N.S. Mian, S. Fletcher, A.P. Longstaff, A. Myers, Efficient thermal error prediction in a machine tool using finite element analysis, Meas. Sci. Technol. **22**, 85–107 (2011)
18. Y. Zhang, J. Yang, H. Jiang, Machine tool thermal error modeling and prediction by grey neural network, Int. J. Adv. Manufact. Technol. **59**, 1065–1072 (2012)
19. A. Abdulshahed, A.P. Longstaff, S. Fletcher, A. Myers, Comparative study of ANN and ANFIS prediction models for thermal error compensation on CNC machine tools, LAMDAMAP 2013
20. B. Bringmann, W. Knapp, Model-based 'chase-the-ball' calibration of a 5-axes machining center, CIRP Ann. Manuf. Technol. **55**, 531–534 (2006)
21. BS ISO 8636-2:2007 Machine tools – Test conditions for bridge-type milling machines – Testing of the accuracy – Part 2: Travelling bridge (gantry-type) machines
22. ISO 10791-3:1998 Test conditions for machining centres – Part 3: Geometric tests for machines with integral indexable or continuous universal heads (vertical Z-axis)
23. A. Forbes, Measurement uncertainty and optimized conformance assessment, Measurement **39**, 808–814 (2006)
24. BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML 1995, Guide to the Expression of Uncertainty in Measurement (International Organisation for Standardisation, Geneva), ISBN 92-67-10188-9
25. A. Balsamo et al., Evaluation of CMM uncertainty through Monte Carlo simulations, CIRP Ann. Manuf. Technol. **48**, 425–428 (1999)