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Comparison of volumetric analysis methods for machine tools with rotary axes

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Abstract

Confidence in the ability of a production machine to meet manufacturing tolerances requires a full understanding of the accuracy of the machine. However, the definition of “the accuracy of the machine” is open to interpretation. Historically, this has been in terms of linear positioning accuracy of an axis with no regard for the other errors of the machine. Industry awareness of the three-dimensional positioning accuracy of a machine over its working envelope has slowly developed to an extent that people are aware that “volumetric accuracy” gives a better estimation of machine performance. However, at present there is no common standard for volumetric errors of machine tools, although several researchers have developed models to predict the effect of the combined errors.

The error model for machines with three Cartesian axes has been well addressed, for example by the use of homogenous transformation matrices. Intuitively, the number of error sources increases with the number of axes present on the machine. The effect of the individual axis geometric errors can become increasingly significant as the chain of dependent axes is extended.

Measurement of the “volumetric error” or its constituents is often restricted to a subset of the errors of the Cartesian axes by solely relying on a laser interferometer for measurement. This leads to a volumetric accuracy figure that neglects the misalignment errors of rotary axes. In more advanced models the accuracy of the rotary axes are considered as a separate geometric problem whose volumetric accuracy is then added to the volumetric accuracy of the Cartesian axes.

This paper considers the geometric errors of some typical machine configurations with both Cartesian and non-Cartesian axes and uses case studies to emphasise the importance of measurement of all the error constituents. Furthermore, it shows the misrepresentation when modelling a five-axis

machine as a three-plus-two error problem. A method by which the five-axis model can be analysed to better represent the machine performance is introduced.

Consideration is also given for thermal and non-rigid influences on the machine volumetric accuracy analysis, both in terms of the uncertainty of the model and the uncertainty during the measurement. The magnitude of these errors can be unexpectedly high and needs to be carefully considered whenever testing volumetric accuracy, with additional tests being recommended.

1 Introduction

The challenge for machine suppliers is the need for tight tolerances under widely varying conditions of speed, acceleration, axis reversal, etc. Control of a machine to microns under these diverse conditions is a challenge that is often not fully appreciated, by even some of the most respected manufacturers.

Although machine tools are complex structures, problems of accuracy can be addressed by simplifying them into a combination of simple structures. Common limitations of research and industry are oversimplification, false assumptions or omission of error sources.

It is well known that the sources of errors of a machine tool can be broken into geometric, dynamic, thermal and non-rigid errors [1]. The effect these have on the machine performance throughout the working volume can be complex, with significant numbers of tests required to identify the full interaction.

Machine metrology has developed significantly in the past twenty years with the advances and commensurate popularity in the ballbar, laser interferometry, laser tracking and in-process probing largely coming about from the rapid increases in portable computing power. The improvements in information gathering have allowed comprehensive amounts of machine data to be captured within a few days, with new technology perhaps proving even more efficient [2, 3]. One of the greatest challenges facing the industry today is the processing and interpretation of the measured data to assess machine capability.

2 Geometric errors of a machine

The “geometric errors” of a machine tool are generally taken to mean the six degrees of freedom of each linear axis and the out-of-squareness between the axes. These errors are generally measured using laser interferometers, electronic levels, granite artefacts and dial test indicators [1], while other devices have been developed to help reduce the time required for measurement such as precision artefact probing [3].

The effect of the geometric errors is to take the regular Cartesian frame and produce a distorted frame as represented in figure 1. The obvious impact is the effect on dimension and form when programming in the nominal Cartesian coordinate frame.

Combining the effects of the individual errors to determine the volumetric accuracy is not a new concept [4]. However, as Wang [5] states, there is no standard definition for the volumetric accuracy. Many researchers have used "the sum of the squares" of the errors or the largest vector error. A more representative method of calculation requires a comparison between the error vector at every point within the machine, however this is computationally intensive to achieve [6].

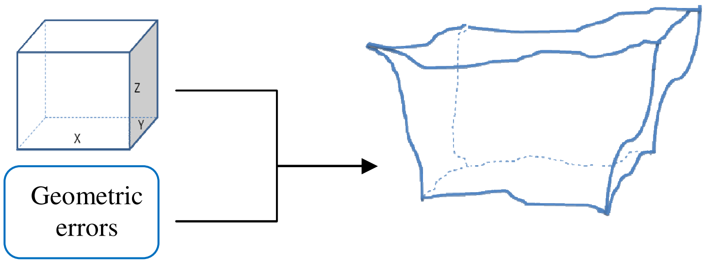

Figure 1: The distorted frame effect of geometric errors

With CNC controllers coming with positional compensation as standard and cross-axis compensation capable of reducing straightness and squareness errors, the largest remaining errors are the angular errors, which have the greatest effect on big machines. Figure 2 shows the angular error of a large gantry machine which, when amplified by one of the perpendicular axes, is 185µm.

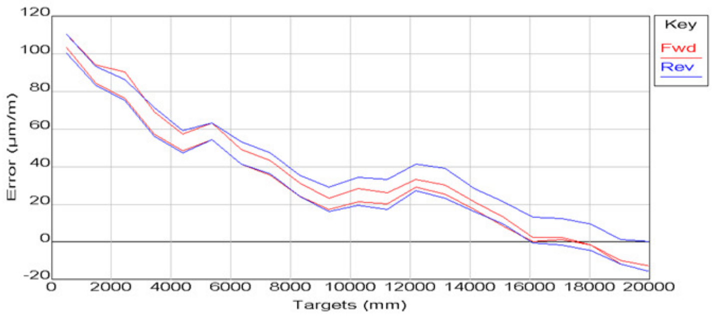

Figure 2: X about Y error on a large gantry machine

3 Volumetric accuracy methods for machines with more than three axes

To reduce measurement time and uncertainty, it is desirable to measure directly the volumetric accuracy of a machine using laser tracking, diagonal laser tests or other means. However, these tests often cannot be applied to machines with additional axes without a large increase in the number of measurements made.

Figure 3 shows two configurations of machines. The left image is a moving column horizontal ram machine with an additional one metre W axis for boring operations. Only by measuring the changing angle of both the Z- and W- axes and synthesising for the different axis combinations can the machine be adequately quantified.

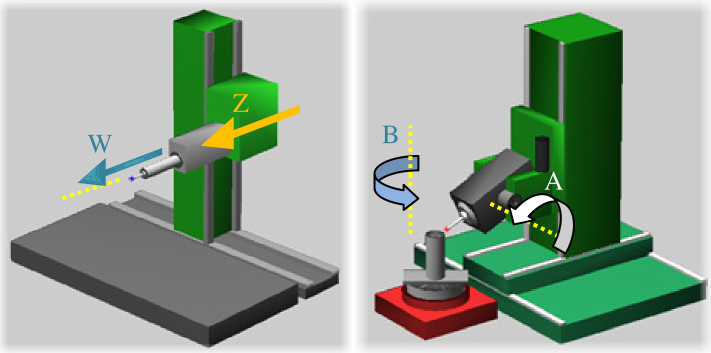

Figure 3. Four and Five axis examples

The right hand image in figure 3 shows a machine with two independent rotary axes. Measurement of these axes using the methods specified in ISO 10791-1 [7] requires care and can be time consuming. Muditha [8] proposes the use of a ballbar and fixture combined with an observation equation to measure all 10 errors with increased efficiency. Simulation work showed an effective identification but the method requires movement of the cartesian axes and the effect of their errors on the method accuracy is not given.

Extending the model to machines with additional axes requires further testing. Obviously the errors of the additional axes need to be taken into account, but the amplification of the Cartesian errors must also be considered. For example, a 3-axis Cartesian machine can have Z-axis rotational error about itself without affecting the accuracy of the machine, since this would only cause the tool to rotate. However, the addition of an axis that can act perpendicular to the Z-axis means that the error becomes significant.

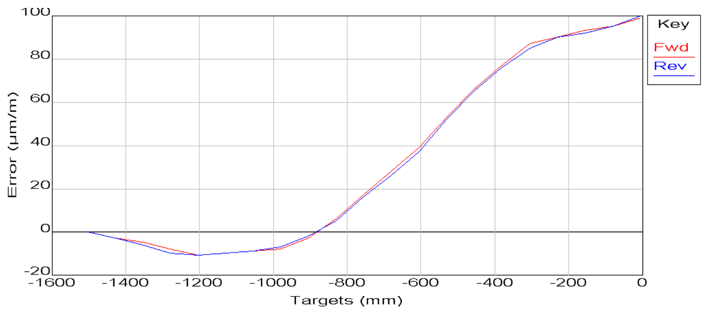

Figure 4: Z axis rotation error about the Z axis

The error for a large gantry machine is shown in figure 4. This error is quite large, with a range of 111µm/m. This has a significant effect of more than 100µm on the machine accuracy because of the offset of the head and tool length.

3.1 Consideration of the universal rotary head

Initial methods of calculating volumetric compensation for a five-axis machine were limited by the computing power of the day. The head errors were treated as a separate problem and their errors quantified using a root mean square calculation, which was then add this to the errors from the Cartesian axes.

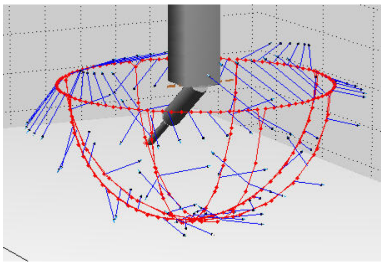

Figure 5: Vector error due to geometric imperfections in a two-axis head

Figure 5 shows the error vectors for different head orientations, considered in isolation from the Cartesian frame. Considering only the RMS is insufficient to truly represent the capability of the head. The error vectors themselves need to be calculated and the capability of the head is given by the worst difference between any two vectors. Table 1 shows the different values obtained by processing measured data in the three different ways listed. It can be seen that the result of the errors can be dramatically underestimated unless a full comparative assessment is performed.

Table 1: Comparison of head error calculation methods for Machine A

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

3.2 Five axis simulation results

For accurate assessment of multi-axis machines, the error at the tool point must be computed at every position in the working volume and with every combination of additional Cartesian and/or rotary axes applied at each of the positions. Using a moderate mesh of twenty-one targets per axis, a three-axis assessment requires over nine thousand evaluation positions. This increases dramatically for additional axes.

For a Cartesian machine with two rotary axes using the same minimum Cartesian step size and a minimum angular step size of ninety degrees requires evaluation at over one hundred thousand positions. To find the maximum difference between any two positions and orientations therefore requires $6x10^9$

comparisons. Without sophisticated simplification techniques [6] this quantity of data processing produces too much data for 3D Cartesian volume assessment, so the traditional approach has been to perform a “3 plus 2” calculation.

Table 2 shows the results of processing measurement data from three machines of different sizes. The effect of the head errors were quite large on each of these machines, which is representative of machines in industrial environments. It can be seen that by using the 3+2 approach can underestimate the volumetric accuracy of the machine by as much as 25%

Table 2: Comparison of volumetric error calculation

	Machine A	Machine B	Machine C
Axis strokes			
X axis	6.0m	18.0m	10.0m
Y axis	3.0m	5.0m	4.0m
Z axis	1.5m	1.5m	1.2m
Error calculation			
3-axis only	252 µm	319 µm	647 µm
Maximum head vector	81 µm	120 µm	241 µm
3-axis + head	333 µm	439 µm	888 µm
5-axis Volumetric Error	417 µm	612 µm	907 µm

4 Uncertainty of the volumetric analysis

The uncertainty of such volumetric analysis comes from the uncertainty of each of the measurements and error terms omitted from the model [9]. Some of these uncertainties can be very significant.

4.1 Thermal errors

Thermal errors affect machine tools in complex ways. Unless the machine is thermally stabilised for expansion and distortion, or the changes are predictable, the measurement of the geometric errors cannot be achieved satisfactorily.

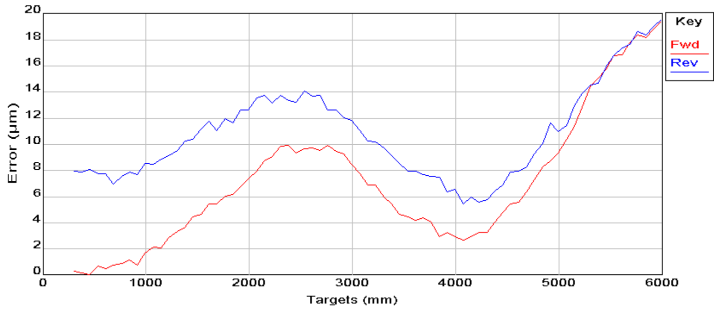

Figure 6: Effect of temperature change on linear positioning

Figure 6 shows a gantry machine whose linear position error has been captured and compensated using the standard CNC linear compensation table. The shape of this residual error is mainly produced by the expansion of axis and expansion of the support columns of the gantry which creates an angular error. It is apparent from the drift during the measurement (8µm at the datum position of X=250) that the machine is continuing to change shape.

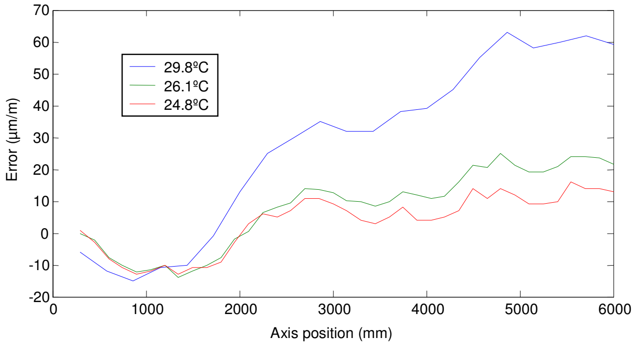

Figure 7: Change in X axis rotation about the Y axis with temperature

Figure 7 shows the change in measured angular error with change in environmental temperature within the workshop. A similar change in profile was also identified in the straightness measurement, with a 60 µm change over the 4°C temperature change (figure 8). Environmental temperature control and thermal compensation would significantly reduce these errors.

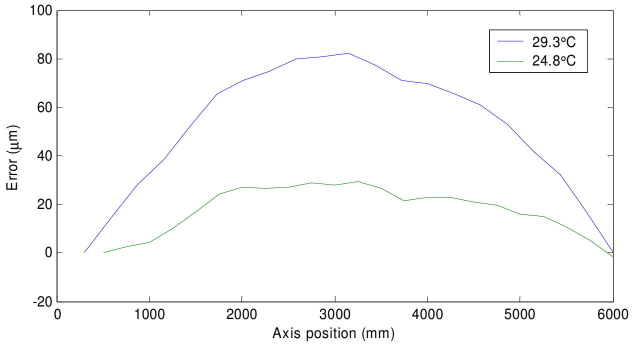

Figure 8. Change in X straightness in Z with temperature

4.2 Non-rigid body errors

Most research simplifies the error model of a machine tool to a rigid-body model. Machine measurement has often yielded results that show that while many machines behave in accordance with the rigid-body assumption, this is by no means universal. It is important that this be proven before a volumetric figure can be presented. Some examples of measured non-rigid behaviour are presented below.

4.2.1 Vertical Turning Lathe

Figure 9 shows the results of measuring the X-axis position of a large vertical lathe at differing Z-axis heights. The positioning error gets worse as the ram is extended (from 42µm to 104µm), because of the pitch error. However, the progression has a non-linear constituent and the axis reversal changes with ram extension, partly because the mechanical support lessens as the ram extends. The maximum reversal error increases from 4µm to 12µm.

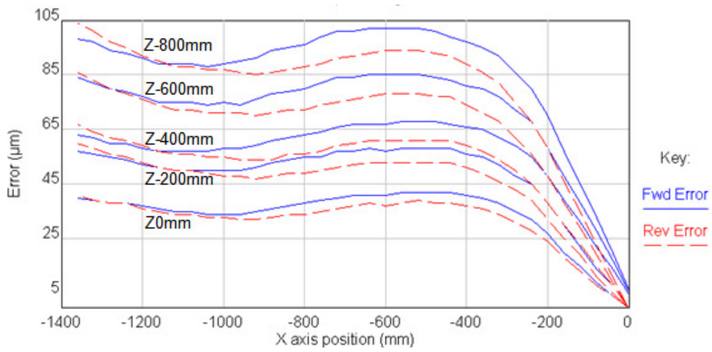

Figure 9: Measurement of the X-axis position error at differing Z-axis heights

4.2.2 Horizontal drilling machine

A series of tests were conducted where the rotation of the nominally stationary head about the horizontal Z axis was measured during rotation of the B axis through the horizontal plane. Figure 10 shows the change in angle measured by an electronic level on the head for the different B axis positions. The range of the error is 28arc-seconds (136µm/m) and the form of the error is clearly asymmetric. Rotation of the ram supporting the C-axis was also measured and this showed a linearly progressive error as did the change in error measured when the W axis was extended. This error is not part of a rigid-body model, so would be omitted when using standard measurement methods.

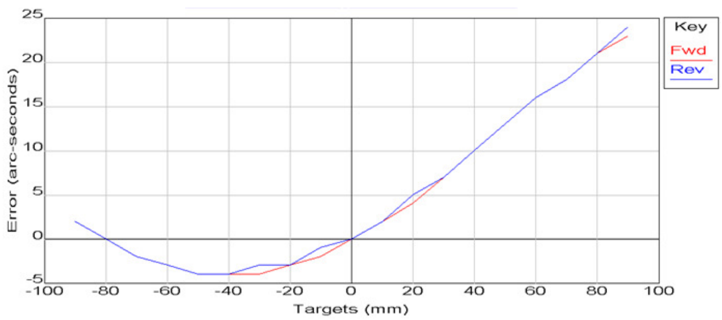

Figure 10: Change in angle of the ram when traversing the B-axis through the horizontal plane

4.2.3 Gantry milling machine

A 5-axis (fork head type) gantry milling machine with an additional W drilling axis parallel to the tool was measured. The A-axis positioning error was measured with the W-axis retracted and extended (figure 11). F1 and R1 are the forward and reverse runs with the W-axis retracted. F2 and R2 represent the profile with the axis extended. It is counter-intuitive that the poorer profile comes from the more mechanically stable configuration.

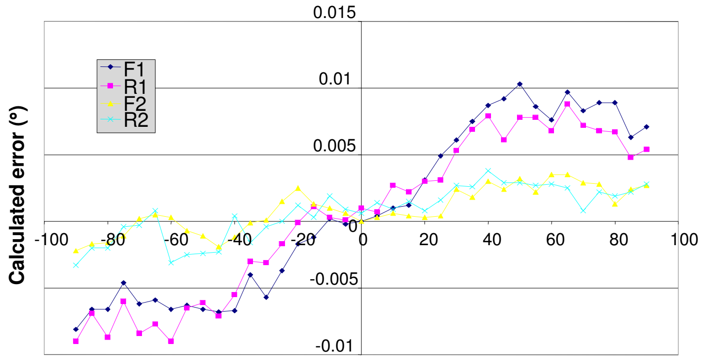

Figure 11: A-axis positioning error with W-axis retracted and fully extended

4.2.4 Horizontal milling machine

A similar configuration to the machine in 4.2.2, this machine was affected by ancillary equipment. An indicator clock was set up to measure a test-bar as the C-axis rotated. The combination of head geometry errors causes the spindle centre-line to be non-concentric. The error measured in an affected direction should give a sinusoidal graph similar to the "expected" trace in figure 12. The machine showed a marked deviation in both the "forward" and "reverse" directions, which is caused by a significant non-rigid influence of ±25µm.

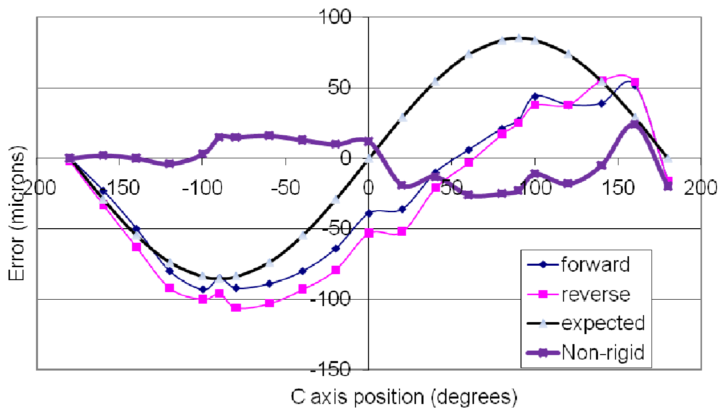

Figure 12: Example of non-rigid behaviour of C-axis rotation

One identified area of uncertainty involves the cable-run that connected the services for the head to the machine. As the C axis rotated, the thick hosing was pulled around generating as much as 40µm/m variation in some measurements.

4.3 Other uncertainties

Other sources of uncertainty of machine accuracy may also need to be considered. For example, quantifying the dynamic performance of the machine in different regions, for different acceleration and deceleration is a time-consuming task. Errors of the spindle itself must also be considered to provide a good indicator of machining capability. Their consideration is outside the scope of this paper.

5 Conclusions

This paper has presented results that show that, in an industrial environment, the head errors of a machine can be a significant contributor to the overall machine accuracy, so the effect of the rotary axes and their errors cannot be ignored.

Calculating volumetric accuracy as the maximum difference between the error vector at any two positions can be computationally intensive. However, analysis of industrial machines has shown that only considering the volumetric error as a "3 plus 2" problem can underestimate the volumetric error by 25%.

Several examples of machine-based uncertainties in the volumetric analysis have been presented in the form of measured thermal and non-rigid behaviour. It can be seen that these errors can be a significant percentage of the rigid-body error, so must be quantified as uncertainties of the final volumetric accuracy figure.

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