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Defining and Computing Machine Tool Accuracy

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Abstract

Understanding machine tool performance is important for specifying or comparing machines and for determining capability for production. Machine accuracy has generally been described by the linear positioning accuracy and repeatability of the axes. This specification neglects all other geometric effects such as angular, straightness and squareness errors which can have a significant effect upon the true precision capability of such machines. A more comprehensive way to define a machine's precision would be to specify the accuracy for the full working volume of a machine tool, i.e. the Volumetric Accuracy (VA) taking into account all geometric errors. Existing methods for describing the volumetric accuracy recognised by the standards organisations are the diagonal and step-diagonal methods. These are designed, in part, to be rapid to reduce machine downtime but compromise accuracy and extensibility if used in isolation. The reduction in accuracy is described in detail in the ISO standard 230 part 6 [1]. This paper describes a definition of VA and a methodology for calculating and reporting the performance of a 3-axis cartesian machine tool that significantly reduces ambiguity compared to other methods and supports a broader range of performance assessments.

Error measurement methods are discussed with respect to accuracy and test time. An example model is discussed highlighting the ease with which 3D positioning error can be calculated then methods for efficiently determining the proposed volumetric accuracy. The method is extensible in that the data and model describe the machine volume completely and therefore enables a variety of performance assessments for machine comparison or process capability. Examples are provided showing the difference in accuracy using variable volume assessments and also an example part profile. The method also enables easy calculation of the percentage contribution of each geometric component at the volume positions most affecting the volumetric accuracy enabling targeted correction with maximum performance benefit.

1 Introduction

Characterisation the positioning capability of machine tools can require a significant amount of effort if it is to be determined for the entire working volume or a subset of the volume. This level of understanding is required if the production capability of the machine is to be assessed or for a more complete comparison between machines. Traditional linear positioning and repeatability figures have, and often still are, used to qualify a machine in terms of positional accuracy. The additional factors, particular the other geometric errors (angle, straightness and squareness) but also thermal errors are affecting many manufacturing industries. Their identification using increasingly available metrology such as Ballbars and laser interferometry systems is exposing a much lower capability of the machines that is often initially communicated.

This shortfall in understanding can have a significant detrimental effect on production systems when they fail to perform as expected and when there is often large outlay associated with machine tools. There can be long term costs associated with concessions and the effort required to maintain the accuracy level compared to a machine that is over capable.

An increased awareness of the factors influencing machine capability has led to an increase in the use of volumetric assessment methods for determining volumetric accuracy (VA). This can be identified using direct measurement or by an error synthesis method.

Direct methods usually involve either on-machine probing of a artefact such as a ball or hole-plate with additional spacers or by a laser tracker which combines measurement of distance and two angles (azimuth and elevation). Generally, artefacts are small and therefore efficiency and accuracy diminishes as multiple positions in a larger volume are measured and the data stitched together. Laser trackers have a large range but the accuracy diminishes with distance. The 3D coordinate uncertainty at a target distance of 10m was estimated from the specifications of three popular tracker systems to range from 70 µm to 136µm.

The ISO 230 part 6 [1] standard provides instructions that have been used for estimating VA from face and body diagonal tests which goes some way to providing a more complete picture of the machine positioning capability. These test are relatively quick to perform but they cannot provide an unambiguous description of the magnitude of the individual contributing error components affecting the tool point in each axis direction [2,3].

Error synthesis methods involve indirect determination of position error by calculating the effect of the individual geometric error components using a complete kinematic model of the machine [4]. This method enables full volume assessment using readily available metrology applied thoughout manufacturing industry such as laser interferometry, inclinometers and artefacts. This paper describes a definition of VA and a methodology for calculating and reporting the performance of a 3-axis cartesian machine tool using this method that significantly reduces ambiguity and supports a broader range of performance assessments.

2 Data collection for indirect method

Using the proposed methodology in this paper requires that all the individual 21 error components (3-axis machine) on the machine need to be measured and this process can be laborious and time consuming depending on the equipment available. Traditional laser interferometers such as the Renishaw's ML10 or HP systems are widely available either in-house or through measurement services and these enable measurement of most of the errors in 1 to 2 days. More recently, multi-degree of freedom systems have been developed such as the API XD6 [8] which can measure all six errors on a axis simultaneously, significantly reducing the measurement time to within 1-day even on large machines. Further reduction in machine downtime is possible using the new software system TRAC-CAL produced by ETALON [9] which, in conjunction with a standard laser tracker or the newly developed LaserTracer, is reported to take between 2 to 4 hours to calibrate a medium 3-axis machine. The measurement principle used by TRAC-CAL is solely based on the use of the laser wavelength and multilateration to calculate all the individual geometric errors thus increasing the accuracy beyond that capable using angle and distance normally used by a single position tracker.

With these systems, it is becoming increasingly efficient to obtain the detailed error data for the indirect volumetric accuracy determination.

3 Transferable model

Describing the rigid body kinematics using homogenous transformation matrices has been shown to be a reliable method of calculating the 3D tool point error using data about the individual error components. It has been commonly applied for error compensation [4, 6, 7].

Avoiding the use of transformation matrices, a machine specific geometric model can be created easily by adding the effects of each contributing error by studying the machine geometry and applying a simple protocol. Each of the measured 21 errors are considered and the effect determined. Figure 1 shows an effect *Ex* resulting from an X axis angular error about a Y axis $\phi y(x)$ (X pitch) and movement of the amplifier axis Z.

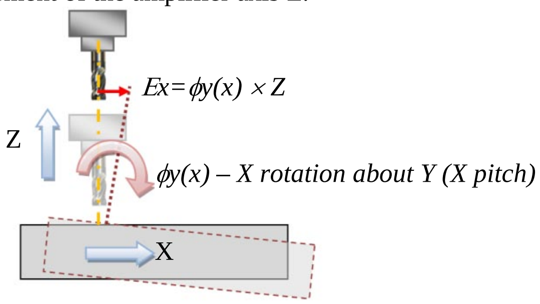

Figure 1. Determining error effects

Figure 2 shows a 3-axis model implemented in Microsoft Excel for a machine with all axes moving the tool (example shown in figure 4). The X, Y and Z axes are the Bottom (B), Middle (M) and Top (T) axes respectively. This hierarchy is determined from the way the axes are stacked [7]. Most common machine tools can be categorised into three distinct configurations based on this hierarchy:

1. All axes move the tool. *wBMTt*.
2. One axis moves the workpiece, two move the tool. *BwMTt*.
3. Two axes move the workpiece, one moves the tool. *BMwTt*.

Where *t* and *w* relate to the tool and workpiece respectively.

X error	X linear	Y in X	Z in X	X ab Y * Z	Y ab Y * Z	X ab Z * Y	XZsqr * Z	XYsqr * M	Xe:
Xe	331.98	-32.193	1.303	9.975	0	61.5	63.35	-231	**204.915**
Y error	Y linear	X in Y	Z in Y	X ab X * Z	Y ab X * Z	YZsqr * Z			Ye:
Ye	9.2	-38.554	-18.188	-2.45	1.51655	8.05			**-40.4255**
Z error	Z linear	X in Z	Yin Z	-X ab X * Y					Ze:
Ze	9.2	-39.759	21.126	21					**11.567**

Figure 2. Geometric model in Excel for wBMTt configuration.

It is important that the effect of the all the errors are added together correctly and therefore a model and measurement protocol is required. Generally, the direction of an error is considered a positive error if the axis used to compensate that error has to move in a negative direction. For linear and straightness errors, shown by the left most diagram in Figure 3, this is simple. For angular errors, the direction of an additional amplifier axis needs to be considered. The middle diagram in figure 3 shows a B axis pitch error (B axis rotation about the T axis), the effect of which is to produce an error in the B axis direction ε_{+B} with a magnitude which is a function of the M axis position. The indicated counter-clockwise error is positive with positive movement of the amplifier. Exceptions to this rule occur when there are two effects from an angle. An example is shown in the right most diagram in figure 3. This is a B-axis roll error (B axis rotation about the B-axis) where an effect occurs in the negative direction. This requires a subtraction in the model as indicated in figure 2 in the Z error equation.

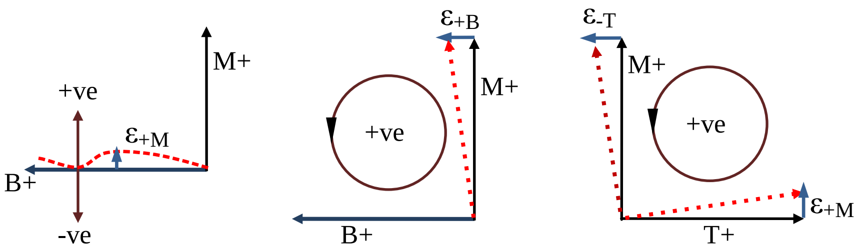

Figure 3. Error measurement protocol diagrams

3.1 Measurement offset positions

The final part of the protocol involves measurement offset positions. Due to Abbé offset, the angular errors have a varying effect on the linear and straightness depending on measurement location i.e the offset position of the perpendicular axes.

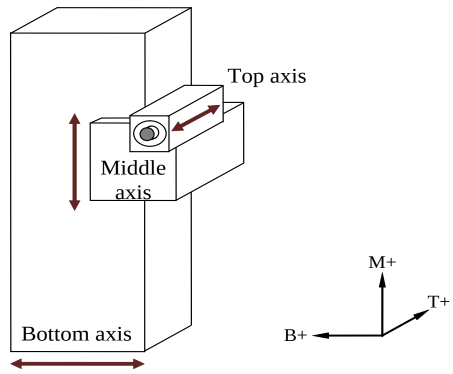

Figure 4. Example machine configuration showing hierarchy

In theory it does not matter where the B axis is positioned for the M and T axis measurements. In practice the B axis will be positioned at mid travel or at some convenient location for mounting the optics. It is good practice to keep the B axis position in the same location for all M and T axis measurements. The B axis is not an amplifier for any angular error component and the axis offset is 0.

The M axis will probably be positioned at a convenient location for mounting the optics for B and T axis measurements. The M axis position should remain the same for all B and T axis measurements. The B axis position error varies as a function of M axis position (and B axis pitch), also the T axis position varies as a function of M axis position (and B axis roll) so the M axis offset is the M position at which the B and T axis linear positioning errors are measured. The M axis position must obviously remain the same for both linear positioning measurements.

The T axis will probably be positioned at a convenient location for mounting the optics for B and M axis measurements. The T axis position should remain the same for all B and M axis measurements. The B axis position error varies as a function of T axis position (and B axis yaw and M axis roll), also the M axis position error varies as a function of T axis position (and B axis roll and M axis pitch) so the T axis offset is the position at which the B and M axis linear positioning errors are measured. The T axis position must obviously remain the same for both linear positioning measurements.

3.2 Loading error data

Most measurement systems can record the data in an ascii file and therefore can be imported easily into software. In the Excel example, position dependent error data can be incorporated and referenced appropriately in the model. This very quickly allows the 3D error to be determined for any position in the working volume. This can immediately provide useful information for specific process capability by comparing errors between positions representing simple component features.

4 Calculating volumetric accuracy

In order to calculate the error for every position in the volume, then it becomes necessary to use nested loops to efficiently carry out the calculations.

A software package was developed by Postlethwaite et al. [7] in order to calculate the volumetric error from data obtained of the individual axis error components. This commercial software uses universal geometric models in order to simulate the effect of the geometric errors over the machine volume for any 3-axis machine with at least one axis moving the tool. The largest error in the specified volume is provided together with a breakdown of how each of the individual error components contributes to the result. This can be a valuable tool for determining where the significant contributors are and assignment of corrective effort.

The calculation of this largest error is dependent on the offset positions of the measurements due mainly to the fact that the angular errors have no calculated effect at these positions. It is therefore possible to derive different values if the measurements are carried out with different offset positions (and therefore different amplification) or different reference points. The errors in the volume are with respect to this offset position and therefore do not provide an indication of error during production if the part or dimension datum's vary, which in production they invariably will.

4.1 Capability assessment

By comparing the difference between two vectors in the volume, we find the errors that would affect production, for example between two features on a part or from a datum to a feature. By comparing every point in the volume with every other point we find all possible combinations of moves and the errors. For a grid resolution of 21targets cubed, there are 9261 points in the volume and almost 43million comparisons. This number can cause problems with memory allocation if the results are to be stored for analysis and visualised. The process can also take several minutes to complete.

A solution has been devised that significantly reduces the number of comparisons by dismissing vectors in the volume that have a similar direction but are smaller than some other. As the vectors are created, they are grouped according to their direction. Two parameters are therefore required. The first is the angular tolerance which determines whether each new calculated vector fits an existing group or needs a new group. The second is a magnitude which is a for comparing the magnitudes of each vector with the largest in a group.

The angular comparison must be sensitive to all 3 directions therefore the X, Y and Z components of each vector are normalised and subtracted from the group mean. The sum of the differences is then compared with the tolerance.

Figure 5 shows a plot containing all vectors calculated in the working volume of a large horizontal machine. Each vector is represented by a cone having both direction and magnitude. A low spatial resolution of 12*8*6 was used to maintain visual clarity.

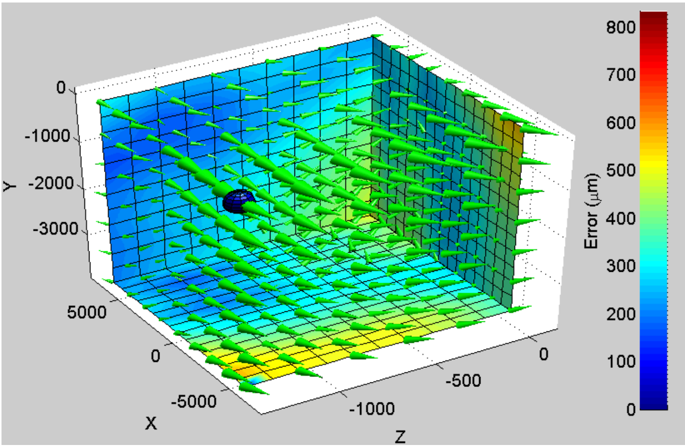

Figure 5: Cone plot showing volumetric error

The number of vectors is 819 which requires 334562 comparisons to find the largest vector difference/ volumetric accuracy of 1306μm. The default magnitude tolerance is 0.9 which gives the comparisons in Table 1.

Table 1. Reduction in vector comparisons

Parameter	Records	Comparisons	≈% reduction
None	819	334562	
0.05	365	41472	88
0.1	192	25992	92
0.2	118	7200	98

Even with the parameter set at 0.2 the calculated volumetric accuracy was within 1%. The significant 88% reduction in comparisons and therefore calculation time means that even with high resolution simulations, more a rapid result. A further consideration is the use of a histogram to show distribution of the vector differences. The left hand chart in Figure 6 is the distribution without reduction whereas the right chart is using the angular tolerance of 0.2. Although the volumetric accuracy was correct, the distribution accuracy has diminished.

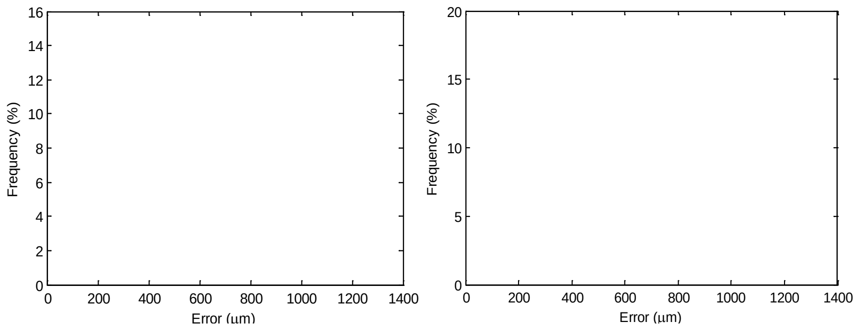

Figure 6. Histogram of volumetric error

Increasing the magnitude tolernce also reduces the calculation time but adversly affects the histogram. Generally a value between 0.8 and 0.9 gives a good compromise.

The methodology is extemely robust and reductions from more than $10x10^6$ to a few thousand comparisons can still give the correct volumetric accuracy.

4.2 Reduced volume

The volumetric accuracy derived from the largest vector difference gives the true machine production capability. This figure is often large and it is very unlikely that two holes, for example, will be drilled at these positions. The histogram also shows that most of the error in the volume is in the region of 250µm. Simply re-running the simulation with reduced traverse range can give a capability more suited to relevant component sizes. Considering a reduction from 12m x 4m x 2m (>100m^3) to 6m x 2m x 1m, the volumetric accuracy reduced from 1306 µm to 380µm.

4.3 Profile simulation

The error synthesis method also allows easy determination of tool point error for specific production profiles such as that shown in figure 7. 3D vectors are shown along the edge of the aerofoil and the X, Y, Z and vector sum errors shown on a chart. It is usual for only one or two directions to be relevant for a particular component feature. Tool paths can be approximated or retrived from a part program as was the case in the example shown. A great deal of care must be taken to consider all factors that could affect the part accuracy during real production such as fixture or part datuming using probing etc.

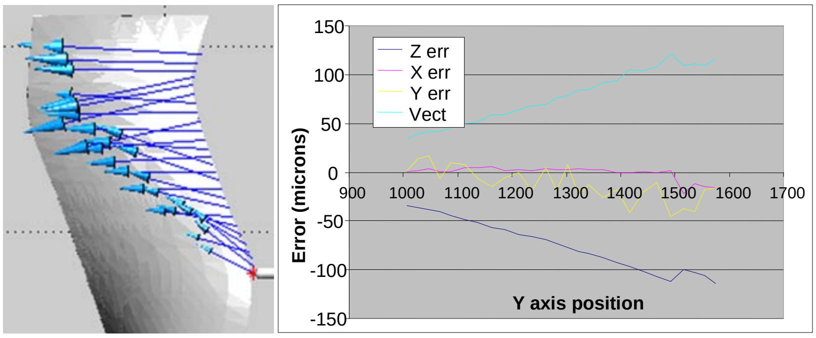

Figure 7. Tool path profile with error vectors and error chart

5 Conclusions

Combining the effects of the individual error components of a cartesian machine tool can enable a machine specific model that allows a accurate determination of the machine volumetric accuracy. In additon a thorough analysis can be made of the machine capability for production. Great care must be taken to assure sign convention. For full analysis of the volume a high-resolution spatial grid needs to be used for comparison of error vectors. Amethod has been devised to reduce computation overhead by grouping similar error vectors. This has a significant speed improvement without affecting simulation exactness.

6 References

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