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Geometric error analysis software for CNC machine tools

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Abstract

In recent years British and International standards have been expanded to cover most aspects of machine tool calibration. Standards now exist for straightness and angular calibration as well as the more conventional linear positioning calibration. Although the standards provide comprehensive guidelines for measurement and analysis of the individual error components they do not define how these errors will affect machine performance. Angular errors in particular are difficult to quantify in terms of how they will affect machine tool accuracy, as this is a function of a number of parameters such as machine configuration and size.

It is a difficult and laborious task to determine the combined effect of all the error components throughout the volume of the machine. But it is this, the volumetric accuracy of the machine, that determines machine performance and is of real interest to the machine builder and user.

To address these problems software has been developed at The University of Huddersfield to calculate the machine volumetric accuracy from the individual geometric error components, and to calculate the effect of machine angular errors. This Windows based software provides a graphical interface that is easy to use. This paper describes the software in detail.

Introduction

Prior to 1991 the main British Standard covering the accuracy assessment of CNC machine tools was BS4656 part 16. The only machine measurement covered by this standard was axis linear positioning [1]. As a result of this linear positioning was the main measurement used by machine builders and users alike to determine the accuracy capability of their machine tools. In many cases linear positioning calibrations were used as key tests for machine pass off. Indeed, the main accuracy specification for many machines was quoted in terms of axis linear positioning capability. In 1991 BS 3800 part 2 was published and included guidelines for the measurement and statistical analysis of axis straightness and angular errors (roll, pitch and yaw) in addition to linear positioning [2]. By including these measurements the standard recognised that machine tool accuracy is a function of all the axis geometric error components.

The guidelines for straightness and angular error measurement were largely based on the established techniques for linear positioning error measurement. The errors are measured statically along an axis at intervals to suit the axis length. A minimum of five measurement runs in each direction is recommended in order for error repeatability and reversal to be determined. The resulting error data is plotted in terms of error value against axis position. Statistical analysis can be performed on the data set to determine confidence bands for the error and to calculate indices used to quantify the error component. These indices include mean error value, mean reversal value, unidirectional and bi-directional repeatability and total error band. It can be seen from this that the standard provides comprehensive techniques for quantifying the magnitude and make up of a particular error component, but it does not attempt to calculate how the error components effect machine performance or how they relate to component accuracy.

Angular Errors and Machine Accuracy

The individual effect of linear positioning error and straightness error on machine performance is in most cases obvious. By studying the error plots directly the implications for machine performance can be determined. For angular error components, however, the problem is far more complex. The error component is measured in terms of angle in arc seconds or maybe µm/m. To determine how the angular error relates to machine positioning performance requires further calculation. The problem is further complicated because the positioning inaccuracy produced by an angular error is a function of three variables, namely:

1. The magnitude of the angular error
2. The length of travel of the machine axes
3. The machine tool configuration

It is perhaps obvious that the size of an angular error will influence its effect on machine tool positioning accuracy, such that the greater the magnitude of the error the bigger its effect. However, the angular component will only produce a positioning error in the machine as the result of movement

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of a second, orthogonal machine axis. For example, consider two machine axes X and Y, where the Y axis is mounted on top of the X. As the X axis moves it experiences small angular errors. The effect of these small rotations is to define a new trajectory for the Y axis. Positioning errors will only be produced when the Y axis starts to move along this new trajectory. The greater the movement of the Y axis the greater the positioning error produced. So in this case the angular error varies as a function of X axis position, and the resulting position error varies as a function of Y axis position. It can be seen from this that studying the angular error in isolation, as defined in the standard, does not provide the complete picture with regard to machine accuracy. In this example if the maximum angular error is 50µm/m (approximately 10 arc seconds) and the maximum stroke of the Y axis is 0.4m, then the maximum resulting position error is 20µm, however if the maximum stroke of the Y axis is 4m then the maximum position error becomes 200µm. So depending on the stroke of the machine's axes what might be considered as a large angular error in numeric terms could be relatively insignificant in terms of machine positioning accuracy. In general terms angular errors are more significant on larger machine tools, to the extent that in many large machines they will be the dominant source of machine geometric inaccuracy.

The final factor influencing how angular errors effect machine positioning is the machine configuration. In this context the machine configuration is the arrangement of its axes and their relationship to the tool and the workpiece. For all practical cases there are only three basic three axis machine tool configurations. In the first configuration the workpiece is stationary and all three axes are associated with movement of the tool. In the second configuration the workpiece is moved by one axis and the tool is moved by the other two axes. In the final configuration the workpiece is moved by two axes and the tool is moved by the third axis. The machine configuration does not influence the size of the resulting position errors but defines which axes experience the position errors. So the same angular error could produce position errors in different axis directions depending on the machine configuration.

Machine Tool Volumetric Accuracy

Although an understanding of the effects of individual geometric error components is important it does not give the full picture with regard to a machine's volumetric accuracy capability. All the geometric error components combine as the machine's axes move through the working volume to produce continually changing position errors in the axis directions. The way in which these error components combine is not trivial. Small individual error components could combine to produce significant positioning errors in the machine volume, conversely large individual error components could combine to produce insignificant positioning errors in the volume. In order to calculate the volumetric accuracy of a machine the user would have to know how the geometric error components combine and then calculate their effect at every point in the machine volume. This is a difficult and laborious task even for a small machine tool. However, a knowledge of a machine's volumetric accuracy would provide a direct indication of its production capability, which is essentially what most machine users wish to know.

The current British and International Standards support the measurement of most geometric error components, but they do not attempt to relate these individual error components to the volumetric positioning capability of the machine tool. The ability to calculate machine volumetric accuracy from the geometric error components could provide the following significant advantages.

- It would provide machine users with valuable information on machine performance that relates directly to a machine's production capability.
- It would provide machine users with a better understanding of the effects of geometric errors, potentially giving a better diagnostic and maintenance capability.
- It would support the standards and encourage the measurement of machine geometric errors.

In order to realise this potential a software package has been written at the University of Huddersfield that can calculate a machine tools volumetric positioning capability from the individual axis geometric error components.

The Geometric Error Analysis Program

This is a Windows based program that can be used to quantify and illustrate the effects of geometric errors on machine tool accuracy in a meaningful and unambiguous way. The Windows environment provides an excellent graphical user interface, making the software easy to use and allowing the data to be displayed in a clear and meaningful way.

The program can calculate the effects of the measured geometric error components throughout the machine volume in order to determine a measure of the volumetric accuracy of the machine. It can also calculate and display the effect of individual angular errors on the overall accuracy of the machine. The program is designed to work with standard geometric error files produced by the Renishaw laser measurement system, however the software could easily be modified to accept data from other measurement systems. It accepts linear positioning error data, straightness error data and angular error data. In addition squareness errors may be entered as discreet values using the computer keyboard.

The program uses geometric models to simulate the affect of the geometric errors throughout the machine volume. The geometric model is developed from

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a kinematic analysis of the machine, and is a set of equations that describe the relationship between the axial position errors, the geometric error components and the axes positions. As was stated earlier the effect of certain error components is sensitive to the machine configuration, and a different geometric model is required for each configuration. The use of a geometric model to calculate axial position errors is an established technique used in many volumetric error compensation systems [4,5,6]. They have also been used in CMM applications to assess measurement capability [7,8]. The geometric models assume that the machine is stiff such that the geometric error components do not change significantly across the volume. This is a valid assumption for most well designed machine tools. Indeed, if the error components did vary significantly across the volume their measurement along specific lines, as recommended in the standards [2,3], would be meaningless.

Use of the Program

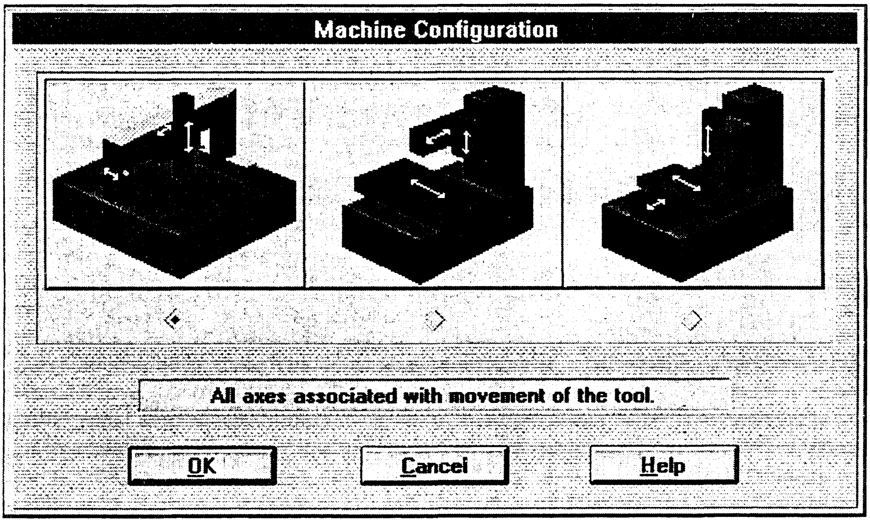
The program operates in a similar way to most Windows programs, with operations being controlled using "pull down menus" or "speed buttons" and information entered using "dialog boxes". During operation brief hints on the purpose of each control are displayed in a status bar at the bottom of the screen. The hints change as the mouse cursor moves over each button or accesses each menu item. When not displaying hints the status bar shows user specific information such as the machine configuration, the working directory and machine name.

When running the software the user is automatically guided through a defined sequence of operations, with certain controls remaining inactive until all previously required operations have been carried out. This logical sequence of operations is defined below, and ensures easy, unambiguous use.

1. Define the machine tool configuration and provide machine specific details.
2. Select geometric error components for use in the simulation, and create error map.
3. Set the simulation parameters.
4. Run volumetric simulation or angular simulation.
5. Analyse and display the simulation results.

Defining a Machine Configuration

This operation allows the user to define a configuration appropriate to a specific machine tool. The software is designed for use with any machine with up to three axes. Initially the user is presented with a standard dialog box and is required to define a directory for the storage of all the machine specific data. If a configuration has previously been defined and stored then the configuration information is automatically loaded. If the machine configuration has not been defined the user is presented with a second dialog box showing three schematic diagrams of the basic machine configurations. The diagrams, shown in figure 1, do not represent particular machines but are included as graphical examples to aid the user and simplify selection. A description of the configuration accompanies each diagram.



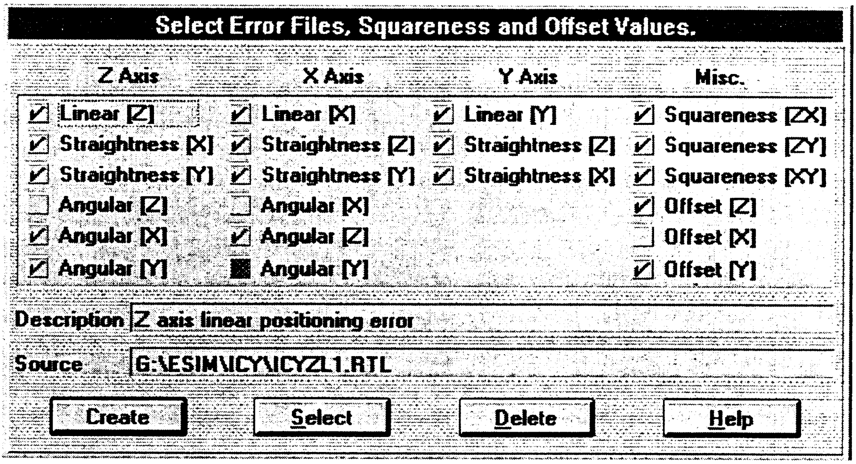
All axes associated with movement of the tool.

Figure 1: Machine Tool Configuration Dialog Box

When the user has selected the appropriate configuration a second dialog box appears showing a single, large diagram of the chosen configuration. This dialog box allows the user to provide machine specific information such as the machine name and the three axis names. The machine name is user definable and may be the machine type, its make or maybe its serial number. In providing this unique identifier the software is customised to the specific machine making the results more meaningful and easier to understand. Unique single character names can also be defined for each machine axis. All the machine specific information is saved to disk in a standard file called *machine.cfg*. This is a fixed file name and cannot be changed.

Selection of Geometric Error Components

With the machine configuration defined the software determines which geometric error components are relevant. When selecting the error components for use in the volumetric or angular simulation the user is initially presented with a dialog box that lists these error components referred to specific machine axes, as shown in figure 2. Once selected a brief description of the chosen error component is shown. The user can then chose to load error component data from a standard Renishaw file stored on disk. A standard Window's open file dialog box automatically lists the appropriate files for the error component selected. If a straightness error has been selected an additional box is provided that allows the line fit, least squares or end point, to be chosen. When a specific error file has been selected the error data is loaded and processed. Processing is required to transform the raw error data to the form suitable for use in the simulation routines.



Z Axis	X Axis	Y Axis	Misc.
☑ Linear [Z]	☑ Linear [X]	☑ Linear [Y]	☑ Squareness [ZX]
☑ Straightness [X]	☑ Straightness [Z]	☑ Straightness [Z]	☑ Squareness [ZY]
☑ Straightness [Y]	☑ Straightness [Y]	☑ Straightness [X]	☑ Squareness [XY]
☐ Angular [Z]	☐ Angular [X]		☑ Offset [Z]
☑ Angular [X]	☑ Angular [Z]		☐ Offset [X]
☑ Angular [Y]	■ Angular [Y]		☑ Offset [Y]

Description: Z axis linear positioning error

Source: G:\ESIM\ICY\ICYZL1.RTL

Figure 2: Geometric Error Data Selection Dialog Box

In addition to axis geometric error components squareness error values can also be loaded for use in the volumetric simulation. In this case each squareness value is entered through the keyboard as a single value in units of μm/m.

When all the required geometric error components have been selected the selection dialog box is closed and an *error map* is automatically created. The error map is a structure in the computer's RAM that holds the processed data from all the selected geometric error files. This error map is used by the program during a simulation to calculate the position errors at any axes co-ordinates.

At this stage the individual geometric error components can be viewed on the screen as text or in graphical form. In text form any of the Renishaw data files can be displayed through a text window. Scrollbars allow the complete file to be viewed, but for data integrity reasons the file cannot be edited. Any of the selected geometric errors may also be plotted graphically as error verses position. Using these features the user can get a complete understanding of the error data without leaving the package.

Setting Simulation Parameters

During simulation the software systematically steps through the machine volume, calculating the axis position errors at each incremental step. The simulation parameters are used to define the machine volume and simulation step size. Again a dialog box allows the user to set all the parameters, such as the travel limits for each axis, the direction of travel for the simulation and the step size to be used in the simulation. The axis travel limits are defined in terms of maximum and minimum axis positions. Using this facility the simulation can be made to run over the complete machine volume or over a reduced volume, maybe defined by a specific component's dimensions. The extremes of travel for each axis are displayed for reference. The simulation can run in either the forward or reverse direction to determine error reversal effects. Separate forward and reverse simulations are included as a single bi-directional simulation would be time consuming to run and would produce results that would be difficult to present in a unambiguous way. A simulation step increment can be set for each axis in units of millimetres. The choice of step size can be important as it determines the resolution of the calculated results, the computer resources required to perform the calculations and the time required to perform the calculations. To aid the user the software can automatically select sensible step sizes for the axes.

Running a Volumetric Simulation

A volumetric simulation is controlled using the volumetric simulation dialog box. Through this dialog box the user can run the volumetric simulation and display and analyse the results. During the simulation process the progression of the calculations is displayed on an indicator bar and by a percentage done indicator.

The results are not displayed until the simulation is completed. At this stage of development the software displays the results as text only. Displaying volumetric error data graphically in a meaningful way is a complex problem requiring three dimensional error data (the position errors in each axis direction) to be displayed within a three dimensional co-ordinate frame. A volumetric simulation dialog box with the results of a simulation is shown in figure 3. Three sets of results are presented for each axis, the algebraic minimum error and its co-ordinates, the algebraic maximum error and its co-ordinates and the error range. The algebraic minimum error is the lowest error calculated for the axis, and the algebraic maximum error is the highest error calculated for the axis. The error range is the difference between the algebraic minimum and algebraic maximum errors for an axis and gives an indication of the total range of error. It can be seen from figure 3 that in addition to the axis specific errors a single figure for volumetric accuracy is provided together with its co-ordinates. Volumetric accuracy is calculated for each point in the

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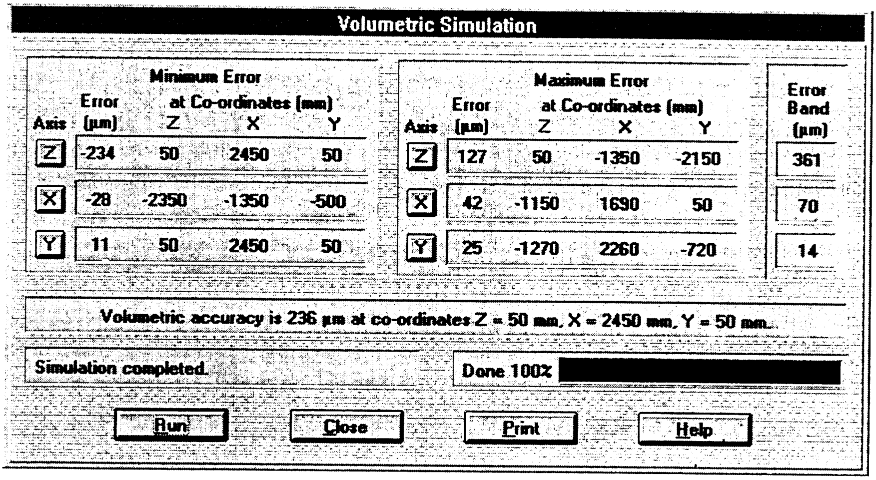
machine volume by taking the vector sum of the three axis errors. The value that is displayed is the largest absolute value that is calculated.



Axis	Minimum Error: Error (µm)	at Co-ordinates (mm): Z	X	Y	Axis	Maximum Error: Error (µm)	at Co-ordinates (mm): Z	X	Y	Error Band (µm)
Z	-234	50	2450	50	Z	127	50	-1350	-2150	361
X	-28	-2350	-1350	-500	X	42	-1150	1690	50	70
Y	11	50	2450	50	Y	25	-1270	2260	-720	14

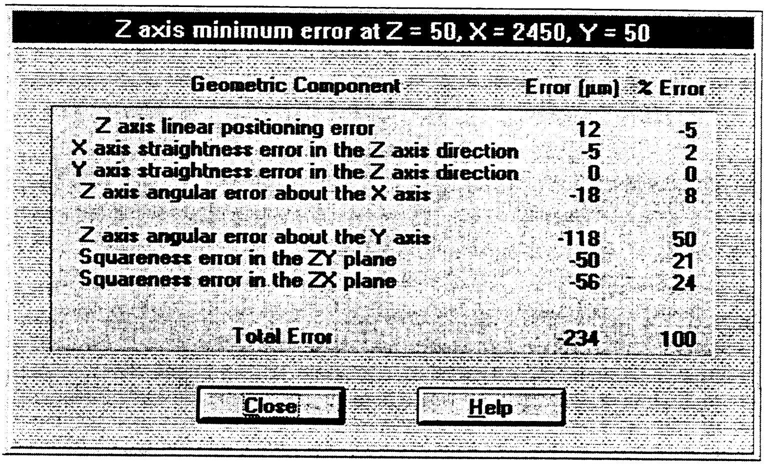
Volumetric accuracy is 236 µm at co-ordinates Z = 50 mm, X = 2450 mm, Y = 50 mm.

Simulation completed.

Done 100%

Figure 3: Volumetric Simulation Dialog Box Showing Results

More detail on the composition of any minimum or maximum error may be displayed by clicking the appropriate axis soft key. This opens a secondary dialog box that provides a break down of the individual error component's contribution to the axis error. An example is shown in figure 4. All the relevant error components are listed and their error contribution is displayed in terms of microns of error and percentage contribution. This feature can be used as a diagnostic tool to determine which error components are significant.



Z axis minimum error at Z = 50, X = 2450, Y = 50

Geometric Component	Error (µm)	% Error
Z axis linear positioning error	12	-5
X axis straightness error in the Z axis direction	-5	2
Y axis straightness error in the Z axis direction	0	0
Z axis angular error about the X axis	-18	8
Z axis angular error about the Y axis	-118	50
Squareness error in the ZY plane	-50	21
Squareness error in the ZX plane	-56	24
Total Error	-234	100

Figure 4: Dialog Box Showing Detail of Axis Position Error

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Running an Angular Simulation

It is not always obvious what effect angular error components have on machine positioning accuracy. To overcome this problem the software can calculate the effect of individual angular errors using an angular simulation. The angular simulation dialog box lists all the relevant angular error components. When an angular error has been chosen a description of the error component is given together with the effects the error component will produce. Some angular errors can produce effects on two machine axes. If the chosen angular error produces two effects then one of the effects must be chosen for simulation. If the angular error produces only one effect the selection is made automatically.

While an angular simulation is running the axes positions are displayed and the progression of the calculations is shown on an indicator bar and by a percentage done indicator. When the simulation is completed a table of position error data is produced in the computer RAM ready for analysis.

Analyse and Display of Angular Simulation Results

The error data produced by an angular simulation is a function of two variables, the position of the primary axis and the position of the amplifier axis. The primary axis is the axis along which the angular error component was measured. The amplifier axis is perpendicular to the primary axis and amplifies the effect of the angular error to produce the position error. The three dimensional simulation data can be examined in any of four ways, tabulated as numeric data, plotted as a 2D graph, plotted as a colour map or plotted as a 3D graph.

In tabular form the error data is displayed numerically in a text window. The primary axis position is displayed horizontally at the top of the table and the amplifier axis position is displayed vertically down the left hand side of the table. If all the error data cannot be displayed within the window scrollbars are automatically placed along the edges of the window.

In 2D graph format the error data is displayed as a conventional two dimensional graph. In this graph the error in microns is plotted on the vertical axis and the primary axis position is plotted on the horizontal axis. The data is plotted as multiple traces with each trace representing a different position of the amplifier axis. A key on the right of the graph indicates the range of travel of the amplifier axis and the step between each trace.

In colour map format the error data is plotted as a rectangular grid of colour. The location of each segment of the grid represents the position of the error, and the colour of each segment represents the magnitude of the error. A colour scale at the right hand side of the colour map indicates the numeric value of each colour in microns of error. The position co-ordinates can be read from scales along the bottom and down the left hand side of the colour map.

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The primary axis position is displayed horizontally and the amplifier axis position is displayed vertically.

In 3D graph format the error data is displayed as a conventional three dimensional graph. On the graph the primary axis position and the amplifier axis position are plotted horizontally and the error in microns is plotted vertically. The error data is represented by the height and colour of the 3D surface. Depending on the shape of the error surface some of the graph may be obscured or difficult to read. In this case the graph may be rotated to change the viewing angle. The graph may be rotated in this way into any of the 4 quadrants.

Conclusions

- British and International standards provide guidelines for the measurement and analysis of individual geometric error components. The standards do not consider how these errors combine to effect machine volumetric accuracy.
- A measure of machine tool volumetric accuracy could provide machine builders and users with a definitive indicator for machine performance, and would allow a machines production capability to be determined.
- The University of Huddersfield has produced a Windows based software package that uses proven techniques to simulate the effect of axis geometric errors on machine volumetric accuracy.

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