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Feature Based Machine Tool Accuracy Analysis method

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Abstract

Machine tool accuracy is the most important performance parameters which affect the part quality. At present, a systematic machine tool accuracy evaluation method is necessary for the machine tool selection in process planning and shop-floor scheduling. This paper proposes an efficient feature based machine tool accuracy analysis method to enable machine tool capability evaluation about accuracy, and the mapping from the machine tool accuracy to the part feature tolerance is established in this method. The cutter is used as a bridge to transform the machine tool error to feature tolerance. The deviation of the cutter between the actual position & orientation and the nominal position & orientation is converted from the machine tool error according to the rigid body kinematics method. Then the feature error in the form of GD&T is calculated from the profile of the feature and the deviation of the cutter. A prototype system has been developed based on this research. An industrial case study shows that the methodology is effective.

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Keywords: Feature, GD&T, Machine tool error, NC machining;

1. Introduction

Due to the strong competition in the market, the R&D cycles and costs of the products are forced to be reduced by the manufacturing enterprises. Whereas for the manufacturing of complex high added-value mechanical products, more and more expensive machine tools with high precision are employed by the manufacturers. How to make best use of these advanced equipments to get the most benefits is a challenged issue. At present, the machine tool selection in process planning and machine tool dispatching in shop-floor scheduling are almost completed by the experienced engineers. But some problems such as equipment idleness, task load unbalance and scheduling changes occurs frequently. With regards to this, some research is undertaken to establish the relationship between machine tools and parts in terms of machining errors. Accuracy is one type of the most important parameters of the machine tool, and determines the part machining errors to a large extent. However, it is difficult to establish the mapping from the machine tool accuracy to the GD/T (geometric dimensioning and tolerancing) of parts.

In this paper, an efficient feature-based machine tool accuracy analysis method is proposed to evaluate the machine tool capability in terms of accuracy. The machining features represent the desired shape with quality requirements reflected by the GD/T. The cutter movement errors are analysed as bridge to establish the mapping from the machine tool accuracy to the GD/T of machining features.

The rest contents of this paper are organized as follows: the research on machine tool error modelling is reviewed in section 2. In section 3, the deviation of the cutter between the actual position & orientation and the nominal position & orientation is converted from the machine tool error according to the rigid body kinematics method. Then the feature error in the form of GD&T is calculated from the profile of the feature and the deviation of the cutter. A prototype system which was developed to verify the method and a simulated verification experiments which is done on a three-axis machine tool are introduced in section 4. The section 5 of the paper is the conclusion.

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2. Literature review

Machine tool error modeling methodology is the basis of the machine tool accuracy analysis, such as in research of the machine tool error identification and compensation [1]. International standard was also issued by ISO or ASME [2, 3] according these research. But the existed methodology only represents the relationship between the measurement result and machine tool kinematic error by mapping from a ball-bar reading to several machine errors. But it is not enough to analysis the relationship between the part GD/T and the machine tool accuracy.

There are some researches which show the relationship between part accuracy and the machine tool accuracy. In 1969, NAS979[4] standard which represent the final performance test for five-axis machining centers was carried out, and then was widely accepted by manufacture enterprises. Soichi Ibaraki [5] indentifies the machine tool error through cutting the several steps on a block directly. Chen Shang-Liang[6] proposed a kinematic errors evaluation method for five-axis machine tool using direct cutting method on a pyramid workpiece, and the kinematic errors of a five-axis machine was evaluated and analyzed from the geometric errors of the cut pyramid workpiece which is measured using Coordinate Measuring Machine (CMM). However, in these researches the influence of cutting conditions was neglected such as different workpiece geometric shape, machining deformation and dynamic cutting force. The methods above are deficient to represent the relationship between the part accuracy and the machine tool accuracy in the practical cutting process.

3. Feature Based machine tool accuracy analysis

Feature is the representation of the engineering meaning or significant of the geometry of a part or an assembly [7]. Part feature is a way to describe different shapes of mechanical parts, and the part accuracy is specified by the geometric dimensioning and tolerancing (GD&T) [2] associated with the part feature. Because the cutter movement is driven by the machine tool components, in this section the cutter movement errors are utilized to establish the mapping between the machine tool accuracy and the parts feature accuracy described by the GD&T. There is a notice that cutter error mentioned below will represent the cutter movement error above as a simplification.

3.1. Transformation from machine tool error to cutter error

In the real environment, error appears when the machine tool axis moves, so the cutter position will deviates from the ideal position. The cutter error contains both the cutter position error and the orientation error. The cutter error could be calculated on different types of machine tool by the method below which is derived by the existed machine tool error model definition [8].

3.1.1 Machine tool error definition model

The machine tool accuracy definition model was first built by the vector expression in 1977 [9]. In 1992 the frequently-used model right now is established [8]. Generally, there are three main sources of errors in machine tools that determine machine tool accuracy. These are: (1) geometric inaccuracies errors; (2) thermally induced errors; and (3) load induced errors. The results caused by these errors are the dimensional and geometric errors of the part in the machining. Geometric error will be considered in this section 3.1, and the thermal error, the load induced error and other factors in the machining process would be considered in section 3.3.

For example the geometric error components of a 3 axes vertical machining center are as Table 1:

Table 1. The geometric error components of a 3 axes vertical machining center

Type of error components	Number of error components
Linear positioning errors (scale error)	3
Straightness errors	6
Angular errors	9
Orthogonality (squareness) errors of machine axes	3
Total	21 error components

Homogenous matrix is generally adopted in the machine tool accuracy definition model [1]. For the components or axis of the machine tool, the error is described by the homogenous transformation matrix as shown by Eq.(1). $\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$ is the errors in rotational degree of freedom (DOF) of a machine tool component, and Δx,Δy,Δz is the error in the translational DOF of a machine tool component.

For a detailed example of the X direction motion component of a vertical 3-axis machine tool, the error homogenous matrix ^{E}Tx will be represented as Eq.(2),where the $\Delta_x(x)$ is the linear position error of the X motion component; $\Delta_y(x)$, $\Delta_z(x)$ is the straightness error; the $\delta_x(x)$,$\delta_y(x)$,$\delta_z(x)$ is the angular error of the X motion component.

For the orthogonality errors of machine axes, take the orthogonality errors between the X motion and Y motion, the homogenous transformation matrix ^{E}Txy is represented as Eq.(3), and ε_{xy} is the orthogonality error values.

Eq.(4) is the homogenous matrix of the X component motion, where the value X in Eq.(4) is motion distance.

For the other machine tool component such as Y direction motion component or Z direction motion component, the relative homogenous matrix is similar as the description above.

$$\begin{bmatrix} 1 & -\Delta\gamma & \Delta\beta & \Delta x \\ \Delta\gamma & 1 & -\Delta\alpha & \Delta y \\ -\Delta\beta & \Delta\alpha & 1 & \Delta z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$^{E}T_x = \begin{bmatrix} 1 & -\delta_z(x) & \delta_y(x) & \Delta_x(x) \\ \delta_z(x) & 1 & -\delta_x(x) & \Delta_y(x) \\ -\delta_y(x) & \delta_x(x) & 1 & \Delta_z(x) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$^{E}T_{xy}=\begin{bmatrix}1 & -\varepsilon_{xy} & 0 & 0\\ \varepsilon_{xy} & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (3)$$

$$T_{x}=\begin{bmatrix}1 & 0 & 0 & X\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (4)$$

3.1.2 Cutter error calculated from machine tool error

The multi-rigid-body methodology [10], which is usually employed in the compensation or identification of the machine error, is an efficient way to combine the machine tool error to the cutter error. Because there are three translational DOF of the cutter and two rotational DOF of the cutter, define the cutter translational error vector W^T is represented as Eq(5),and cutter rotational error vector W^R is represented as Eq(6), E_X, E_Y, E_Z, E_A, E_B is the five errors of the cutter respectively in each DOF.

$$W^{T}=[E_x \quad E_y \quad E_z \quad 1]^T \quad (5)$$

$$W^{R}=[E_A \quad E_B \quad 0 \quad 1]^T \quad (6)$$

Take a vertical 3-axis gantry machine tool with the removable gantry as an example, the cutter translational error will be calculated by Eq.(7) based on the multi-rigid-body methodology and the homogenous matrix tool described in section 3.1.1. More expatiation of the Eq.(7) could be learned in literature [1].

$$W^{T}=T_x\bullet{}^{E}T_x\bullet{}^{E}T_{xy}\bullet T_y\bullet{}^{E}T_y\bullet{}^{E}T_{yz}\bullet{}^{E}T_{xz}\bullet{}^{E}T_z\bullet T_z\bullet{}^{E}T_{sz}\bullet T_s\bullet{}^{E}T_s\bullet P_0 \quad (7)$$

Where $P_0=[0,0,0,1]^T$ as the initial vector.

Also, the rotational error vector W^R would be calculated by the same manner. The total error of the cutter is deduced as in the Eq.(8). The resultant formula describes the deviation of the tool position and the tool direction from it is nominal position caused by the machine tool errors. There is a notice that the higher order terms are neglected for the resultant error.

$$\begin{cases} E_x=\Delta_x(x)+\Delta_x(y)+\Delta_x(z)-Y\bullet\delta_z(x)-\varepsilon_{yx}\bullet Y+\varepsilon_{xz}\bullet Z+(\delta_y(x)+\delta_y(y)+\delta_y(z)\bullet(Z-L)-\varepsilon_{xs}\bullet L+\Delta_x(s)\\ E_y=\Delta_y(x)+\Delta_y(y)+\Delta_y(z)-\varepsilon_{yz}\bullet Z-(\delta_x(x)+\delta_x(y)+\delta_x(z))\bullet(Z-L)+\varepsilon_{ys}\bullet L+\Delta_y(s)\\ E_z=\Delta_z(x)+\Delta_z(y)+\Delta_z(z)+\delta_x(x)\bullet Y+\Delta_z(s)\\ E_A=-\delta_x(x)-\delta_x(y)-\varepsilon_{ys}-\delta_x(z)\\ E_B=\delta_y(x)+\delta_y(y)+\varepsilon_{xs}+\delta_y(z)\end{cases} \quad (8)$$

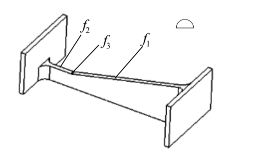
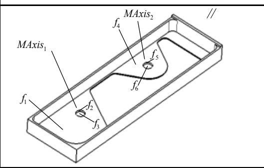
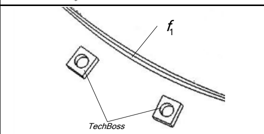
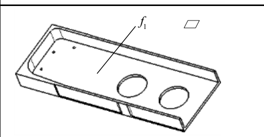
3.2. Transformation from cutter error to feature geometric tolerance

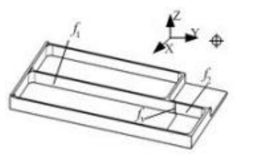
After the cutter error is obtained, the relationship between the cutter error and the feature geometric tolerance is established then as below.

3.2.1 Feature geometric tolerance

Take the aircraft structural parts as an example, some feature geometric dimensioning and tolerancing (GD&T) elements which are applied as the parts inspection requirements [11] are listed in Table 2. The feature errors caused by the cutter error will be evaluated according to the form of the feature geometric tolerance in next section.

Table 2 Examples of feature for aircraft structural parts

Feature	Schematic	Associated Geometry	Inspection Process
Height of rib		$Geo=f_1\cup f_2\bigcup f_3$, on the top of the rib	Inspection with a fixed three machine
Parallelism		$Geo=MAxis_1\cup MAxis_2$ $MAxis_1=f_1\cup f_2\cup f_3$ $MAxis_2=f_4\cup f_5\cup f_6$, Always hole, in the pocket	Inspecting the hole to get hole axis, then get the parallelism.
Profile of a surface		$Geo=f_1$, Always the outer profile	The inspection axis direction is in accordance with the inspected face. Avoid the collision to the technique boss
Flatness		$Geo=f_1$, Always the bottom of the pocket	Inspection with a fixed three machine, one point by one point.

positional Tolerance of Rib		$Geo = f_1 \cup f_2 \cup f_3$ Always the side of the rib, also as the wall of the pocket.	The inspection axis direction is in accordance with the inspected face.

3.2.2 The basic transformation from cutter error to feature geometric tolerance

According to the tolerance requirement below as the example, this section will introduce the transformation from cutter error to feature geometric error. Firstly, take the flatness of the plane when is processing by end milling as an example for error calculation.

For a plane machined by end milling, the movements of the cutter tool bottom face form the plane. The position of bottom face is determined by the cutter, and the inclination of the bottom face will form the plane flatness error. So the situation should be divided into two case as shown in Fig.1.

1) In Fig.1 (a), the plane position error derives from the component position error. In Fig.1 (b), it also derives from the machine component orientation error because the cutter length amplifies the rotational error. This postion error is caused by the cutter translational error in the Z direction which means cutter error E_z in section 3.1.2.

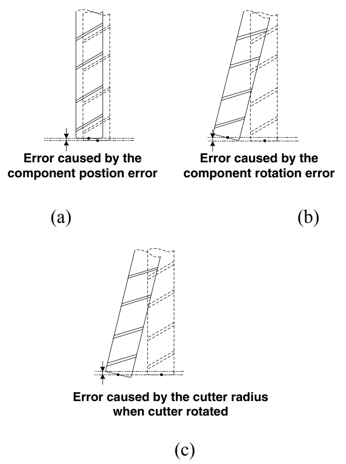


Fig. 1 The plane error schematic

2) In Fig.1(c), the cutting edge is higher or lower than the cutter tool centre. It is rather important that when the cutter tool is in the tilt status. The error is caused by the cutter radius, so the plane will contain the error:

$$E_A \cdot R + E_B \cdot R \quad (9)$$

Combining the status 1) and 2), the plane position error finally is:

$$E_Z + E_A \cdot R + E_B \cdot R. \quad (10)$$

If the cutter error is derived from a 3-axis machine tool such as in section 3.1.2, then combined with Eq. (8),

The tolerance result will be

$$E_Z + E_A \cdot R + E_B \cdot R = \Delta z(x) + \Delta z(y) + \Delta z(z) + Y \cdot \delta x(x) + [\delta_x(x) + \delta_x(y) + \delta_x(z) + \varepsilon_{yz}] \cdot R + [\delta_y(x) + \delta_y(y) + \delta_y(z) + \varepsilon_{xz}] \cdot R \quad (11)$$

The error of the flatness of the plane when in the process of flank milling, or the error of the height of the rib could be calculated in the same method above.

3.2.3 The enhanced method deriving from basic transformation

For the tolerance with datum reference, the datum reference is also a feature processing by the machine tool on the part. The method in section 3.2.2 is not fit for these more complex feature tolerances. Parallelism error of two cylinders will be the case to state the methodology below.

1) The error of the cylinder surface

For a cylinder machined through drill, milling or boring, the position of the cutter tool bottom is the key to forming the cylinder. The position of cylinder is determined by the cutter， and the inclination of the side edge of the tool will form the cylinder error. The both situation is shown as Fig.2.

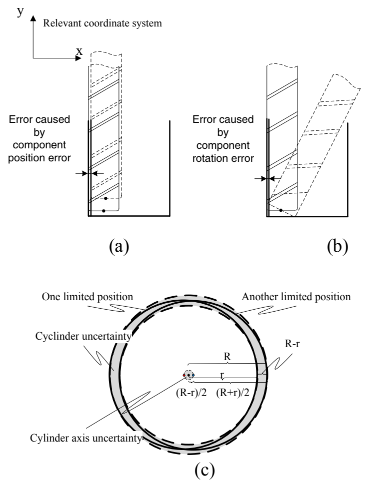


Fig. 2 The cylinder error schematic

In Fig.2 (a), the plane position error derives from the component position error. In Fig.2 (b), it derives from the machine component rotation error because the cutter tool contains the tool length.

$$Ex + R \bullet (1 - \cos E_B)^2 \quad (12)$$

But the cylinder error is caused by both the X direction and Y direction. So the resultant error is as follows.

$$\sqrt{(Ex + R \bullet (1 - \cos E_B)^2 + (Ey + R \bullet (1 - \cos E_A))^2} \quad (13)$$

Then, according to the Fig.2(c), the error of the cylinder axis, which will be used below, is as follows.

$$E_{uc} = (\sqrt{Ex + R \bullet (1 - \cos E_B)^2 + (Ey + R \bullet (1 - \cos E_A))^2}) / 2 \quad (14)$$

2) The parallelism error between two cylinder surfaces

According to the definition of the parallelism error, the schematic of the two cylinders with error is shown in Fig.3. The Parallelism error is calculated as follows.

$$E_{up} = \frac{2 \bullet E_{uc}\sqrt{L^2 - E_{uc}{}^2}}{L} \tag{15}$$

Besides, some geometrical tolerance, which is not introduced below, but the method is similarly as the content above.

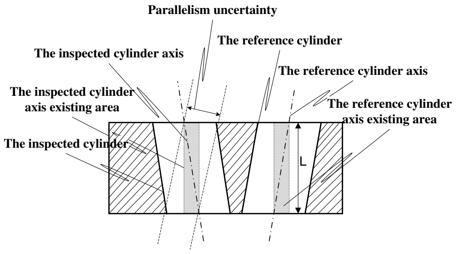


Fig. 3 Parallelism error schematic

3.3. Machine tool accuracy analysis through the calculated geometric error and existed geometric tolerance

The geometric errors are employed in the methodology. In fact, many factors affect the machining accuracy such as thermal errors, cutting force induced errors, servo errors,tool wear in the machining process, the part deformation and setup error. Some errors such as thermal error could be used in the methodology above like the geometric errors.

The thermal errors are the geometric errors which are caused by the changes of the thermal fields of the machine tools. Corresponding to 21 geometric errors with machine tool at cold start, there are 30 thermally induced errors in the three axis machine tool, among which 18 geometric errors are thermally and position-dependent and 12 geometric errors are only thermally dependent, For a detailed example of the X direction motion component of a vertical 3-axis machine tool, the homogenous matrix both describing geometric error and the thermal error is shown as below.

$$\begin{bmatrix} 1 & -\delta_{zT}(x) & \delta_{yT}(x) & \Delta_x(x)+\Delta_{xT}(x) \\ \delta_{zT}(x) & 1 & -\delta_{xT}(s) & \Delta_y(x)+\Delta_{yT}(x) \\ -\delta_{yT}(x) & \delta_{xT}(x) & 1 & \Delta_z(x)+\Delta_{zT}(x) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{16}$$

$$\begin{bmatrix} 1 & -\varepsilon_{xyT} & 0 & 0 \\ \varepsilon_{xyT} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{17}$$

Where $\Delta_x(x)$ is the linear position error; $\Delta_y(x)$, $\Delta_z(x)$ is the straightness error; the $\delta_{xT}(x)$,$\delta_{yT}(x)$,$\delta_{zT}(x)$ is the angular error of the X motion component induced by thermal. $\Delta_{xT}(x)$, $\Delta_{xT}(y)$, $\Delta_{xT}(z)$ are thermal drift. ε_{xyT} is the orthogonality error values induced by thermal and position.

According to the multi-body method, the cutter tool error could be calculated from the thermal error above such as in section 3.1.2. And then the calculation from the cutter error to feature error is the same as the description in section 3.2.2 and 3.2.3.

But in the practical the thermal error is time varying, getting a maximal or average value of thermal error is costly to be measured than geometry error, also the other errors affecting the machining accuracy could not be measured under the current condition. Hence, a preliminary statistics strategy is considered by us to fill the gap. Considering the condition of the average process ability and stable machine tool errors, according the existed research conclusion by Callaghan [12], when the feature machining tolerancing is less than the calculated feature machining error from the machine tool static error, obviously, the machine tool could not be fit for machining of the feature. When the feature machining tolerancing is one to four amount of the calculated feature machining error, inspection needs to be done to ensure the machining accuracy, because the dynamic error could not be neglected. When the feature machining tolerancing is the four amount of the calculated error, the machine is fit for the machining, because of the dynamic errors and static errors are all considered by the statistical safety coefficient. Then this make the calculated geometric error could be directly used in machine tool accuracy evaluation.

4. Case study

A prototype system based on this research is developed. The inputs of the system are existed machine tool error value and required feature GD&T, and the outputs are the safety coefficient which represent the machine tool accuracy capability and a error list which represents the relationship between the part accuracy and the machine tool accuracy. For the process planner, according to the required part feature accuracy and the existed machine tool accuracy condition, the machine tool capability is predicated. When the machine tool could not meet the requirement, equipment with higher accuracy is necessary. And if the part feature accuracy requirement is easy to be achieved, the machine tool also could be changed to assign the machine tool reasonably. The user interfaces of the system are shown as in Fig.4.

The dynamic error cause that the proposed method cannot be verified by the cutting experiment very well. Therefore, a virtual simulated experiment is designed. In the simulated environment, the machine tool is ideal. The machining errors caused by the machine tool errors are embedded into the tool path in the post process, then the machining simulation result will show the machining quality of the part feature. The experiment is executed on the machining simulation software VERICUT™ shown as shown in Fig.5.

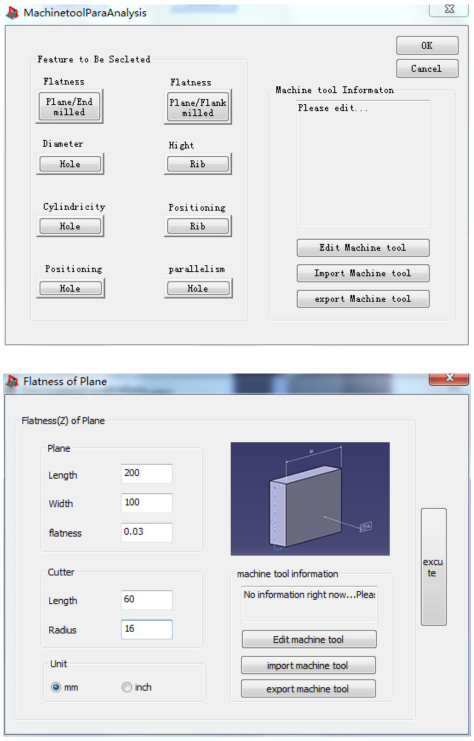


Fig. 4 The user interface of the developed system

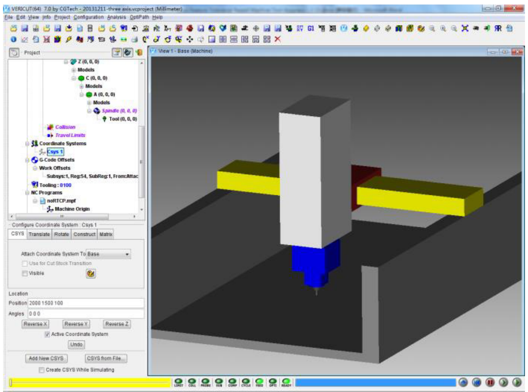


Fig. 5 Simulation environment in VERICUT^{TM}

After machining simulation, the features are measured by the AUTO-DIFF function in the simulation environment as shown in Fig.6. The regions marked in red are the overcut areas caused by the machine error, and the regions marked in blue are the uncut areas. The original kinematic error of the machine tool is shown in Table 3. The values of feature errors from the simulated experiment and the values calculated by the proposed research are compared in Table 4. The deviations between the measured errors in the simulation and the calculated errors are very tiny, and it shows that the proposed method is effective.

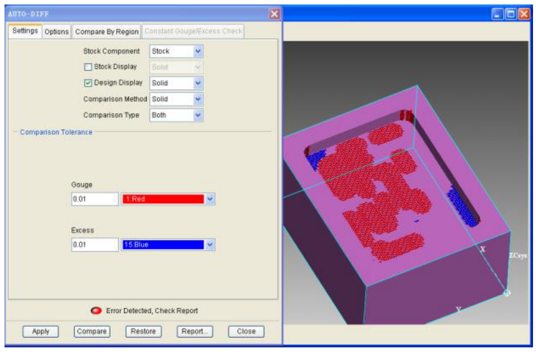


Fig .6 Measurement by AUTO-DIFF function in the simulation

Table 3. The error list of the machine tool in the experiment

Index	Error	description	Angular value (mm/mm)	Positional value (mm)
1	Δx(x)	Linear	N/A	0.02
2	Δy(x)	Straitness	N/A	0.02
3	Δz(x)	Straitness	N/A	0.02
4	δx(x)	Angular	0.015/1000	N/A
5	δy(x)	Angular	0.020/1000	N/A
6	δz(x)	Angular	0.020/1000	N/A
7	εxy	Orthogonality	0.015/1000	N/A
8	Δy(y)	Linear	N/A	0.02
9	Δx(y)	Straitness	N/A	0.03
10	Δz(y)	Straitness	N/A	0.03
11	δy(y)	Angular	0.002/1000	N/A
12	δx(y)	Angular	0.020/1000	N/A
13	δz(y)	Angular	0.020/1000	N/A
14	εyz	Orthogonality	0.020/1000	N/A
15	Δz(z)	Linear	N/A	0.015
16	Δy(z)	Straitness	N/A	0.015
17	Δx(z)	Straitness	N/A	0.015
18	δz(z)	Angular	0.030/1000	N/A
19	δy(z)	Angular	0.030/1000	N/A
20	δx(z)	Angular	0.030/1000	N/A
21	εxz	Orthogonality	0.025/1000	N/A
22	Δx(s)	Radical	N/A	0.025
23	Δy(s)	Radical	N/A	0.025
24	Δz(s)	Axial	N/A	0.02
25	εxs	Angular	0.025/1000	N/A
26	εys	Angular	0.025/1000	N/A

Table 4. Comparison between simulated value and calculated value

Type of feature tolerance	Value of simulated error (mm)	Value of calculated error (mm)

Flatness of end milled plane	0.051	0.047
Flatness of flank milled plane	0.060	0.061
Cylindricity of hole	0.044	0.042
Parallelism of two hole	0.061	0.055

Conclusion

This paper proposes the feature based machine tool accuracy analysis method which establishes the mapping between the part feature accuracy and machine tool accuracy to evaluate machine tool capability. The cutter is utilized as a bridge for the kinematic transformation and the geometrical relationship construction in the method. The deviation of the cutter between the actual position & orientation and the nominal position & orientation is converted from the machine tool error according to the rigid body kinematics method. Then the feature error in the form of GD&T is calculated from the profile of the feature and the deviation of the cutter. The method was implemented on a three-axis machining centre. A prototype system is developed and a relative test shows that the methodology is effective.

This paper only employs the existed statistics conclusion in establishing the machine tool capability evaluation to avoid the interferential factor of the methodology. The extension of the present research could be the mechanism of the statistics strategy in practical cutting process, and this could make the evaluation methodology more accurate.

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