Title:

Experimental Study on Cutter Deflection in Multi-axis NC Machining

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Abstract: In five-axis sculptured surface machining, the effect of cutter deflection on tool orientation planning is important. This paper studied the method for online measurement of cutter deflections along two axes simulation. The measurement equipment was designed and implemented to acquire the displacements of cutter under cutting force online. Acquired data were processed to static values and then compensated by geometric analysis. The cutter deflection conditions were analyzed and divided into different types. The corresponding geometrical equations of the relationship of deflections of measured values and actual values were built. The inter-coupling values were decoupled by solving the geometrical equations. The changing regulations of cutter deflection with tool orientations were analyzed, which could provide support for the study of tool orientation planning. The effectiveness of measurement error compensation was verified by the difference between measured values and actual values of cutter deflections under various tool- workpiece inclination angles. This work could be further employed to optimize tool orientations for suppressing the surface errors due to cutter deflections and achieving higher machining accuracy.
Experimental Study on Cutter Deflection in Multi-axis NC Machining

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Keywords: experimental study, cutter deflection, multi-axis machining, online measurement.

1 Introduction

Five-axis machining provides machine tool with two rotation axes to enlarge accessible space of the cutter, which meets the needs of machining sculptured surface

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such as aeronautical components. By planning tool orientations, it is probable to avoid interference among cutter, workpiece and other parts, raise the contact order between tool envelope surface and design surface of workpiece to increase machining efficiency, and so forth [1]. Most crucial parts of aeronautical components, such as compressor impeller, landing gear, and rocket engine shell, possess not only complicated surface but also ultra-high strength material. That can engender great cutting force acting on the multi-axis machining system which contains long kinematic chains. Meantime, the cutting tool usually works in an abnormal posture relative to the normal vector of the surface at the cutter contact (CC) point. These conditions all probably produce noteworthy cutter deflection that may make serious consequences. Generally, cutter deflection is the more major issue of sources suppressing the machining precision compared with tool wear, cutter run-out, and chatter vibration [2, 3]. Large cutter deflection can bring about unacceptable machining surface errors and restrict the improvement of production efficiency, or even destroy the machining system.

Series of research have been carried out on the prediction of cutting force induced cutter deflection as follows. Landon predicted the cutter deflection without using the cutting force model, in which a data block was created for each machine/mill/material from experiments [4]. That method only aimed to concrete cases for three-axis milling applications. Dow et al. [5] calculated the deflection of small ball-end mill, and also only considered the flexibilities of the tool and spindle. Chanal et al. [6] computed the cutter deflection due to static structure deflection based on machine structure and cutting load, in which one-tooth flat-end mill and drill were adopted and both considered as a solid body. Besides, the structure model aimed to parallel kinematics machine of tricept legs and was not depicted concretely, and the cutting pressures were identified experimentally. Dépincé et al. [7] dealt with calculation of tool deflection in flat-end milling in which only the cutting force modeling was proposed. Wang et al. [8] described the modeling of robot deformation caused by the external process forces from the machining applications which was only a conceptual model. Soori et al. [9] presented a virtual machining system in order to enforce tool deflection in three-axis milling operations in which only the flexibility of the cutter was computed. Rodríguez et al. [10] developed a tool deflection model based on the tool geometry and elasticity theory of the material, which was used for two- and three-axis micro-milling processes.

As mentioned above, some took the cutting tool as rigid body, another took the spindle and the handle (or tool-holder) as rigid body, and most did not take the transmission axes into account. Furthermore, precise experimental verification of the model was lacking. Most models could only be used for three-axis machining which did not take advantage of five-axis machining fully, or did not connect it with lead and tilt angles for tool orientation planning. As the continuation of our preliminary studies on geometrical error analysis and machine tool characteristic [11, 12],
the main purpose of this paper was to present a method, which could precisely measure the cutter deflections and study the variety discipline of cutter deflection under variable tool orientations in five-axis end milling. Then tool orientation planning based on cutter deflection model could be implemented easily.

The remainder of this paper was structured as follows. In section 2, the online measurement equipment for obtaining cutter deflections was described. That was followed by Analysis of measurement errors in section 3.1. Compensation of measurement errors was studied in section 3.2. In section 3.3, comparison and analysis of uncompensated and compensated values of cutter deflection was explained. The whole paper was concluded in section 4.

2 Online Measurement of Cutter Deflections

The equipment to measure cutter deflections online was shown in Fig. 1. There were four modules, namely machining system, clamping system, laser displacement measurement system, and data acquisition system. The cutting tool was the end of the machining system and the component under measurement. The milling center was a five-axis machine tool whose type was Mikron UCP 800 Duro. The two rotation axes of the milling center were at the end of the workbench. So tool orientation towards the machine tool of this structure was actually tool-workpiece relative orientation. The function of the clamping system was to fix the heads to the spindle nose (translates and does not rotate with the spindle) in the way that laser emission direction of one head passed through the tool axis along x axis and that of the other along y axis. In addition, the heads holder of the clamping system could be adjusted along tool axis to make the laser point was right on the lowest part of the shank, and the distance between the emission point reflection point was always within the measurement range of the heads. The laser displacement measurement system was a CCD ultra-high accuracy non-contact laser displacement device and contained two heads (Keyence LK-H020), two head-to-controller cable (Keyence CB-A5), one controller (Keyence LK-G5001V), and a power supply (Keyence MS2-H50). The screen of the heads was protected from high-speed chips by fixing ultrathin gorilla screens to maintain high transparency. The data acquisition system was made up by a computer, a high-bandwidth backplane (NI PXIe-1082), a dynamic signal acquisition card (NI PXIe-4499), and LabVIEW software.

The workpiece material was 300M steel which possessed ultra-high strength and was widely adopted in the aviation industry. The purpose was to make the cutter deflections as big as possible. The machining experiments were performed as shown in Fig. 1. The main geometrical and process conditions in experiments were listed as follows. In the experiments, the diameter of shank of the cutting tool was 10mm;
the radius of arc surface of the cutter was 2mm; the number of flutes of the cutter was 4; the nominal helix angle of the cutter was -50 deg; the length of the tool was 100mm; the length of the flute was 30mm; the feed rate per tooth was 0.04mm; the spindle speed was 1000rev/min; the cutting depth 1.4mm; the milling mode was down milling, and no cutting fluid was used.

To study the regularity of the tool-workpiece inclination angles and cutter deflections, the experiment was designed into several groups with different lead angles and tilt angles. Concretely, all groups were divided into five sets, and each set was divided into four groups. The detailed grouping situation was as follows.

The lead angle, $\alpha$, was set within {0, 10, 20, 30, 40}, and for each of these lead angles, the tilt angle, $\beta$, was varied within {0, 15, 30, 45, 60}. Visibly, except the first group, there were four lead angles and five tilt angles, and 20 groups were combined altogether.

The surface of the workpiece was divided into five regions. The lead angles were the same within each region and different between each pair of region. Further, each region was divided into several paths, and the tilt angles were different between each pair path within a region.

Fig. 1. Cutter deflection online measurement equipment
3 Analysis and Compensation of Measurement Error

3.1 Analysis of Measurement Errors

The shank of the cutting tool was cylindrical surface, which made deflections along x axis and y axis were inter-coupling. In detail, deflection along x or y axis could brought about change of measured value along y or x axis, and the changed value was just measurement error which should be calculated and compensated. Here equations of geometrical relationship between measured values and actual values were built and solved to compensate the measurement errors.

During machining process, there were nine possibilities of cutter deflection directions combination along \( x_t \) and \( y_t \) axes. The nine conditions were shown in Fig. 2 which were divided by the positive and negative of cutter deflections. Necessarily, an assumption should be pointed that the values of cutter deflections all smaller that the radius of the cutter, which was general condition in the actual processing. In Fig. 2, the circles represented cross sections along \( z' \) axis at the optical reflection point of the cutter, and the points represented intersection of the cross section and the tool axis. The blue circle represented cross section of the cutter before deviating from initial position, and the green circle represented that after deviating from initial position. The blue point represented the initial position of the cutter, and the green point represented the deviated position. In the fifth condition, the deviated position overlapped with the initial position, which meant the cutter did not deflected and was an ideal case. The rest eight conditions could be divided into two types by if there existed cutter deflection equaling to zero along \( x_t \) or \( y_t \) axis.

Fig. 2. Nine conditions that the cutter deflects
The first type contained the second, fourth, sixth, and eighth conditions, and an example was shown in Fig. 3, in which there were only cutter deflection along x axis. At first, we set that the directions of lasers emitted were along positive y axis and negative x axis respectively in all conditions. Then concrete analysis for the condition in Fig. 3 was given as follows.

For condition of Fig. 3, $O_1$ represented the initial position of the cutter and $O_2$ represented the deflected position of that. The distance of $O_1$ and $O_2$ was just the actual deflection along x axis ($e_x$). The distance of rightmost points on both the two circle was the measured deflection along x axis ($e_{xm}$). Obviously, the measured value in x direction ($e_{xm}$) equaled actual value ($e_x$). There was no measurement error along x axis in this condition ($e_x'=0$). In y direction, we denoted the initial reflection point by $B$, and the reflection point after the cutter deflected by A. Then the length of $AB$ was both the measured deflection ($e_{ym}$) and measurement error ($e_y'$) along y axis. The actual value in y direction ($e_y$) equaled zero, and the measured value in y direction ($e_{ym}$) was measurement error. In practice, it was unknown what kind the condition was, so the measured value in y direction was used to determine that. According to the Pythagorean Theorem and considering the uncertain environmental error, the equation could be given by

$$\rho - e_{ym} \leq e_{xm} - \rho$$

where $m_0$ was an custom small quantity.

By determination equation mentioned above, when deflection in one direction was small enough, we could treat that condition this type, or it should be handled as followed type.

![Fig. 3. condition when the cutter deflects along only one axis](image)

The second type contained the first, third, fifth, and seventh conditions, and an example was shown in Fig. 4. There were cutter deflections along both x axis and y
axis. Likewise, the lasers were set in directions along positive y axis and negative x axis respectively in all conditions. Then geometrical equations between measured and actual distances could be established as follows.

For condition of Fig. 4, $e_x$ was the length of $AO_2$; $e_y$ was the length of $CO_2$; $e_{xm}$ was the length of $DE$; and $e_{ym}$ was the length of $BF$. By geometrical analysis of them, two equations could be obtained in $RT \triangle BAO_2$ and $RT \triangle DCO_2$ respectively as

$$
\begin{align*}
(\rho - e_{ym} + e_y)^2 + e_x^2 &= \rho^2 \quad (RT \triangle BAO_2) \\
(\rho + e_x - e_{xm})^2 + e_y^2 &= \rho^2 \quad (RT \triangle DCO_2)
\end{align*}
$$

Fig. 4. Condition when the cutter deflects along both two axes

3.2 Compensation of Measurement Errors

To reveal the solution of the geometrical equation for measurement errors compensation, the solutions were given as

$$
\begin{align*}
e_x &= \frac{EX_1 \pm \sqrt{EX_2}}{2EX_3}, \\
e_y &= \frac{EY_1 \pm \sqrt{EY_2}}{2EY_3},
\end{align*}
$$

where $EX_1$, $EX_2$, $EX_3$, $EY_1$, $EY_2$, and $EY_3$ were intermediate variables and given as
\[ EX_1 = 2\rho^3 + 4\rho^2 e_{xm} + 2\rho^2 e_{ym} + 3\rho e_{xm}^2 + \rho e_{ym}^2 + 2\rho e_{xm} e_{ym} + e_{xm}^3 + e_{ym} e_{ym}^2, \]
\[ EX_2 = 4\rho^6 + 8\rho^5 e_{ym} - 4\rho^4 e_{xm}^2 - 8\rho^4 e_{ym} e_{ym} - 4\rho^3 e_{xm}^3 - 12\rho^3 e_{ym}^2 e_{ym} - 20\rho^3 e_{xm} e_{ym}^2 \]
\[-12\rho^3 e_{ym}^3 - \rho^2 e_{xm}^4 - 8\rho^2 e_{xm}^3 e_{ym} - 14\rho^2 e_{xm}^2 e_{ym}^2 - 16\rho^2 e_{xm} e_{ym}^3 - 13\rho^2 e_{ym}^4 \]
\[-2\rho e_{xm} e_{ym} - 4\rho e_{xm}^3 e_{ym}^2 - 8\rho e_{xm}^2 e_{ym}^3 - 4\rho e_{xm} e_{ym}^4 - 6\rho e_{ym}^5 - e_{xm}^4 e_{ym}^2 \]
\[-2e_{xm}^2 e_{ym}^4 - e_{ym}^6, \]
\[ EX_3 = 2\rho^2 + 2\rho e_{xm} + 2\rho e_{ym} + e_{xm}^2 + e_{ym}^2, \]
\[ EY_1 = 2\rho^3 + 4\rho^2 e_{ym} + 2\rho^2 e_{xm} + 3\rho e_{ym}^2 + \rho e_{xm}^2 + 2\rho e_{xm} e_{ym} + e_{ym}^3 + e_{xm} e_{ym}^2, \]
\[ EY_2 = 4\rho^6 + 8\rho^5 e_{ym} - 4\rho^4 e_{xm}^2 - 8\rho^4 e_{ym} e_{ym} - 4\rho^3 e_{xm}^3 - 12\rho^3 e_{ym}^2 e_{ym} - 20\rho^3 e_{xm} e_{ym}^2 \]
\[-12\rho^3 e_{ym}^3 - \rho^2 e_{xm}^4 - 8\rho^2 e_{xm}^3 e_{ym} - 14\rho^2 e_{xm}^2 e_{ym}^2 - 16\rho^2 e_{xm} e_{ym}^3 - 13\rho^2 e_{ym}^4 \]
\[-2\rho e_{ym} e_{xm} - 4\rho e_{ym}^3 e_{xm}^2 - 8\rho e_{ym}^2 e_{xm}^3 - 4\rho e_{ym} e_{xm}^4 - 6\rho e_{xm}^5 - e_{ym}^4 e_{xm}^2 \]
\[-2e_{ym}^2 e_{xm}^4 - e_{xm}^6, \]
\[ EY_3 = 2\rho^2 + 2\rho e_{ym} + 2\rho e_{xm} + e_{ym}^2 + e_{xm}^2, \]

Then it could be reached to calculate the error compensation values along \( x \) and \( y \) axis \( e_x' \) and \( e_y' \) as

\[
\begin{align*}
  e_x' &= e_{xm} - e_x, \\
  e_y' &= e_{ym} - e_y.
\end{align*}
\]

### 3.3 Comparison of Uncompensated and Compensated Values

As shown in Fig. 5, uncompensated values of cutter deflections were indicated by solid lines, and compensated values of them were indicated by dotted lines. Differences between the uncompensated and compensated values varied with the tool-workpiece inclination angles. To express these differences and the relationship with inclination angles more clearly, figures of measurement error and measurement error ratio were also given as follows. The changing regulations of the uncompensated and compensated values with the lead angles and tilt angles were roughly same. The compensated deflections were taken as examples to analyze the general variation trend. From these figures, \( e_x \) varied from 0.1mm to 0.35mm in general. And \( e_y \) varied from 0.2mm to 0.35mm except groups of conditions when \( \alpha = 0 \). It indicated that \( e_x \) increased with \( \alpha \) in the range of test parameters when \( \beta \) was given from the figure.
The changing trends of uncompensated and compensated values along y axis were shown in Fig. 6. Being different from those along x axis, compensated values were bigger than uncompensated values along y axis. Likewise, differences between the uncompensated and compensated values varied with the lead angles and tilt angles. The changing regulations of the uncompensated and compensated values with the lead angles and tilt angles were roughly same. The compensated deflections were taken as examples to analyze the general variation trend.

Fig. 6. Comparison of uncompensated and compensated cutter deflections along y axis
4 Conclusions

In this paper, a method of measuring cutter deflections online involving tool–workpiece inclination angles in five-axis machining was proposed. Study of measurement errors compensation was done to analysis the effect of them.

From the measurement during machining experiments, the cutter deflections in two directions were both the minimum when the tool orientation overlapped with the normal vector at the cutter contact point, but that condition could not meet the actual needs especially in multi-axis machining. Within the scope of experimental parameters, cutter deflection in x direction would decrease with increasing lead angle when the tilt angle was constant, and increase with increasing tilt angle when the lead angle was constant; cutter deflection in y direction would also decrease with increasing lead angle when the tilt angle was constant, and increase with decreasing tilt angle when the lead angle was constant.

From the measurement error compensation and analysis, the changing regulations of measurement errors along x axis basically conformed to those of cutter deflections along y axis, and the general trends of measurement errors along y axis were symmetrical along horizontal direction with those of cutter deflections along x axis. The changing regulations of the uncompensated and compensated values with the lead angles and tilt angles were roughly same. Differences between the uncompensated and compensated values varied with the lead angles and tilt angles.

Based on the proposed method of cutter deflection measurement involving lead and tilt angle, next research will be tool orientation planning for multi-axis NC machining of sculptured surface. An optimized tool orientation space in which the tool orientations can be selected arbitrarily and the cutter deflection is within acceptable limits will be generated. It also provides support for the study of predicting the surface errors due to cutter deflections accurately.

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