Prediction of Machining Accuracy of 5-Axis Machine Tools with Kinematic Errors

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Abstract. Kinematic errors due to geometric inaccuracies in 5-axis machine tools cause deviations in tool positions and orientation from commanded values, which consequently affect geometric accuracy of the machined surface. The present research work studies the prediction of machining accuracy of a 5-axis machine tool with its kinematic errors. First, kinematic errors associated with linear and rotary axes of a 5-axis machine tool with tilting rotary table type, are identified by a DBB method. By using an error model of the machine tool, erroneous tool position and orientations are computed. Then, machining error with respect to the nomial geometry is predicted and evaluated. In an aim to improve geometric accuracy of the machined surface, an error compensation for tool position and orientation is also presented. As an example, the machining of a tilted taper cone by using a straight end mill, as described in the standard NAS979, is considered in case studies to experimentally verify the prediction and the compensation of machining errors in 5-axis machining.

1.1 Introduction

With a tremendously increasing need for machined components with geometric complexity and high dimensional accuracy, 5-axis machine tools are extensively used in the manufacturing of dies and molds, and aerospace parts. Because of having its versatile functionalities, a 5-axis mache tool offers notable benefits including increased material removal rate, enhanced surface accuracy, and reduced effective machining time. However, it is well known that kinematic errors due to geometric inaccuracies of structural components in a 5-axis machine tool can cause signifincant errors on the tool position and the orientation with respect to workpiece, hence leading to a geometric inaccuracy of machined surface in actual cutting operation.

In the past, numerous research works has been carried out to realize kinematic errors, and to simulate and improve motion accuracy of 5-axis machine tools. These works attempted to mainly build up an error model with kinematic errors, and then to predict the motion accuracy of the machine tool (e.g. [1]). There are also many works reported on the identification of kinematic errors on a 5-axis machine tool. Among them, the schemes using the telescopic double ball bar (DBB) measuring device have been widely accepted (e.g. [2]). More recently, a 3D probe ball device [3] is also used to identify some link errors of a 5-axis machine tool.

While the research work reviewed above has focused on the measurement of kinematic errors and the evaluation of motion accuracy of machine tools, no or little work is available in the literature, focusing on the prediction of machining accuracy with kinematic errors in 5-axis machine tools. Unlike conventional 3-axis machines, it is very difficult to intuitively understand the effect of kinematic errors on a 5-axis machine on the machining accuracy, since the motion of a 5-axis machine is generally quite complex. In the industry of 5-axis machine tool builders, the NAS979 standard [4], the machining of a tilted taper cone, is widely known and is often conducted to investigate the machining accuracy of a 5-axis machine tool. However, it is generally quite difficult to diagnose error sources of the machine from error profiles of the machined taper cone. As a basis to establish such a diagnosis methodology from machining results, and to implement a compensation scheme of the machine's motion errors, it is important to understand the effect of kinematic errors on the machining error.

To this goal, the present research work proposes a simulator of machining errors in 5-axis machining with the effects of kinematic errors due to geometric inaccuracies of 5-axis machine tools. Three squareness errors associated with linear axes and eight kinematic errors associated with rotary axes are evaluated and considered in the present study. At first, these total eleven kinematic errors for a 5-axis machine tool of tilting rotary table type are practically identified by the telescopic DBB measuring device. Then, machining errors with respect to the nominal geometry are predicted and evaluated to realize the effects of kinematic errors. In order to enhance geometric accuracy of machined surface, an error compensation for tool position and orientation is also presented. As an example, the machining of a tilted taper cone by using a straight end mill, as described in the standard NAS979, is considered in case studies to experimentally verify the prediction and the compensation of machining errors in 5-axis machining.

1.2 Kinematic Errors in 5-axis Machine Tools

1.2.1 Definitions of Kinematic Errors

In this study, a 5-axis machine tool with a tiltling rotary table is considerd as the target. Figure 1.1 shows the basic configuration of the machine tool. The machine contains three linear axes (**X**, **Y**, **Z**) for generating linear motions in *X*, *Y*, and *Z* directions and two rotary axes (**A**,**C**) for generating rotary motions on the tilting-rotary table about *X* and *Z* axes respectively.

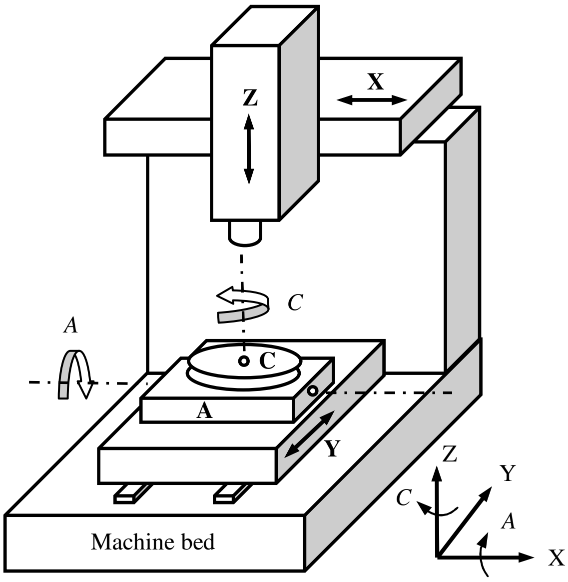

Figure 1.1. 5-axis machine tool with a tilting rotary table

Inasaki et al. [5] have pointed out that there are 11 kinematic errors associated linear and rotary axes in this type of 5-axis machine tool; namely eight kinematic errors (α_{AY}, β_{AY}, γ_{AY}, β_{CA}, δx_{AY}, δy_{AY}, δz_{AY}, δy_{CA}) associated with rotary axes and three kinematic errors (γ_{XY}, α_{YZ}, β_{ZX}) associated with linear axes. The basic definitions of these kinematic errors are as follows; α_{AY}: the angular error of **A**-axis with respect to **Y**-axis about *X*-axis. Similarly, β_{AY} and γ_{AY} are angular errors of **A**-axis about *Y* and *Z*-axes respectively. β_{CA}: is the angular error of **C**-axis with respect to **A**-axis about *X* axis. δx_{AY}, δy_{AY}, and δz_{AY} are linear shifts of **A**-axis from **Y**-axis in *X*, *Y* and *Z* directions respectively. δy_{CA} is the linear shift of **C**-axis with respect to **A**-axis in *Y* direction. γ_{XY}, α_{YZ}, and β_{ZX} are defined as the perpendicularity or squareness errors of three linear axes (**XYZ**) on *X-Y*, *Y-Z*, and *Z-X* planes respectively. These eleven kinematic errors will be considered in error modeling of the machine tool and then, effects of them on machining accuracy will be evaluated as well.

1.2.2 Identification of Kinematic Errors

In this study, a DBB measurement method is applied to identify the above kinematic errors considered. The DBB method already specified in ISO20-1 has recently been applied to the measurement of linear and angular kinematic errors existing in 5-axis machine tools. A number of DBB tests with specific measurement patterns proposed by Tsutsumi and Saito [6] are conducted to identify kinematic errors. The details of the measurement system and procedures for estimating the kinematic errors can be found in [6].

1.3 Error Modeling of 5-axis Machine Tool

According to the coordinate system and kinematic chain of the target machine tool as shown in Fig. 1.1, an error model is established. A brief description of the error model is given as follows:

Consider, an initial coordinate of the tool tip, $p_t^0 = [0001]^T$, and for a command tool path trajectory, the position, $(\hat{X}_c \hat{Y}_c \hat{Z}_c)$ and orientation $(\hat{A}_c \hat{C}_c)$ of the tool tip in reference coordinate is given, the position of tool tip with kinematic errors associated with liner axes, ${}^r p_t$ can be obtained as:

$${}^r p_t = {}^r T_t p_t^0$$

where, ${}^r T_t$ is a 4x4 erroneous homogeneous transformation matrix (HTM) due to kinematic errors, and can be expressed as:

$${}^r T_t = D^1(\hat{X}_c) D^6(\gamma_{XY}) D^2(\hat{Y}_c) D^4(\alpha_{YZ}) D^5(\beta_{ZX}) D^3(\hat{Z}_c)$$

where, $D^{1\text{-}6}(*)$ represent the 4x4 HTMs for purely linear and rotary motions. The left-side superscript *r* denotes vector in reference coordinate, while right-side subscript, *t* and *c* indicate tool tip and command tool tip location respectively.

Then, by taking 8 kinematic errors associated with rotary axes into account, the erroneous position of tool tip in workpiece coordinate, ${}^w p_t$ can be obtained as:

$${}^w p_t = ({}^r T_w)^{-1} ({}^r p_t)$$

where, ${}^r T_w$ is a 4x4 erroneous HTM due to kinematic errors, and can be expressed as:

$${}^r T_w = {}^r T_a {}^a T_c$$

The HTMs, ${}^a T_c$ and ${}^r T_a$ can be obtained as:

$${}^a T_c = D^2(\delta y_{CA}) D^5(\beta_{CA}) D^6(\hat{C}_C)$$

$${}^r T_a = D^1(\delta x_{AY}) D^2(\delta y_{AY}) D^3(\delta z_{AY}) D^4(\alpha_{AY}) D^5(\beta_{AY}) D^6(\gamma_{AY}) D^4(\hat{A}_C)$$

Hence, the matrix ${}^w p_t$ contains tool positioning errors in workpiece coordinate and will generate erroneous tool position due to existing kinematic errors in a 5-axis machine tool.

1.4 Computation of Machining Errors

By using the above error model, once the erroneous tool position and orientation for a tool path trajectory is given, the next step is to compute machining error on workpiece surface. In this study, as an example, 5-axis machining of a tilted taper cone (NAS979) is assumed to be carried. Hence a simple and easy procedure to compute machining errors with respect to nominal geometry of the taper cone workpiece surface is presented. The detailed algorithm for computation of machining errors is given as follows:

(1) Given a set of points on a nominal surface of workpiece, $W_i (i = 1, \ldots, N_w)$, let's define the vectors normal

to those points of the surface, $\vec{v}_{w,i}(i=1,...,N_w)$ as can be shown in Fig. 1.2.

(2) Let's consider a plane made by the tool axis vector, $\vec{v}_{t,j}$ and the tool motion direction vector, $\vec{M}_{t,j}$ for two successive points on the tool path trajectory, $p_j^w(j=1,...,N_p)$. Then the plane is shifted toward the nominal workpiece surface by an amount of tool radius, r (see also Fig. 1.2).

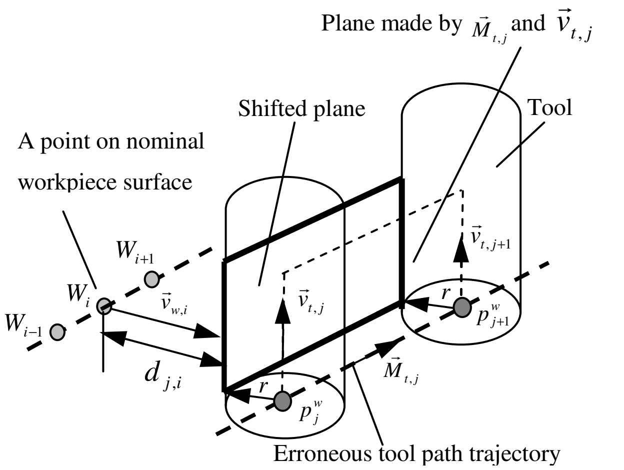

Figure 1.2. Algorithm for computation of machining error

(3) For a point, p_j^w on the tool path trajectory, calculate the distance, $d_{j,i}$ between the shifted plane and a point, W_i on the nominal workpiece surface along the normal vector, $\vec{v}_{w,i}$.

(4) For a point, p_j^w on the tool path trajectory and all the points on the nominal workpiece surface, $W_i(i=1,...,N_w)$, similarly calculate the distances, $d_{j,i}$. Then find the minimum distance, **min** $d_{j,i}$. This is the machining error on the nominal workpiece surface for a point, p_j^w on the tool path trajectory.

(5) Similarly for all the points on the tool path trajectory, $p_j^w(j=1,...,N_p)$, repeat the steps (2)-(4). This will lead to the whole computation of the machining errors on the nominal workpiece surface.

1.5 Case Studies

In this work, two case studies are demonstrated to evaluate the effects of kinematic errors and hence, to justify the prediction of machining errors in 5-axis machining. As an example, the machining of a tilted taper cone workpiece as specified in NAS979 is considered in this study. Figure 1.3 shows the 5-axis machining configuration and different parameters of the taper cone workpiece. In Fig. 1.3, D, θ, and φ are defined as the diameter of tool path trajectory in workpiece coordinate, taper angle, and tilt angle about X-axis of the taper cone respectively, while (C_x,C_y,C_z) is the center location of workpiece on the work-table. H_t and H_b are heights of the taper cone and base cylinder.

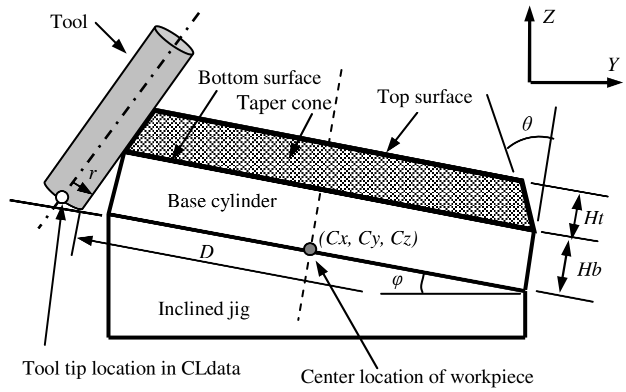

Figure 1.3. Machining configuration and parameters of taper cone

Table 1.1. Identified kinematic errors by DBB tests

8 kinematic errors with rotary axes		**3 squareness errors with linear axes**	
Error parameter	value	Error parameter	value
α_{AY}	+0.0001°	γ_{XY}	-0.0034°
β_{AY}	-0.0071°	α_{YZ}	+0.0054°
γ_{AY}	-0.0081°	β_{ZX}	+0.0037°
β_{CA}	+0.006°		
δx_{AY}	+0.10 μm		
δy_{AY}	- 4.0 μm		
δz_{AY}	+2.8 μm		
δy_{CA}	+3.4 μm		

1.5.1 Prediction of Machining Errors and Experiments

The machining test is conducted by using a commercial 5-axis machine tool with the configuration shown in Fig. 1.1. First, kinematic errors of this machine are experimentally identified by using the methodology presented in Section 1.2.2. Table 1.1 summarizes the identified kinematic errors.

For case study I, machining errors on the bottom and top surface of the taper cone are simulated with the following machining conditions: D=210mm, θ=30°, φ=15°, (C_x,C_y,C_z)=(0,-100mm,53mm), H_t=20mm, and H_b=30mm. Then, using the above machining parameters of the taper cone, actual cutting test with a straight end mill is carried out. Aluminum alloy, a soft material, is used as the taper cone workpiece. Spindle speed of 5500min^{-1}, feedrate of 1000 mm/min, and tool radius of 10 mm are used in cutting test. Conservative feedrate and soft workpiece material are chosen to reduce effects of cutting process (e.g. cutting force, tool deflection, etc) on machining accuracy. After cutting test, surface measurements taken by a roundness measuring device (Talycenta1000) are carried out to measure machining errors on bottom and top surfaces of the machined taper cone workpiece surface.

Figure 1.4 shows simulated and measured machining error trajectories for bottom and top surface of the taper cone with respect to its nominal surface. It is seen from Fig. 1.4 that kinematic errors in 5-axis machine tool have significant effects on machining accuracy. Also, simulated machining error trajectories well agree with measured trajectories.

Case study II is carried out at another set of parameters of the taper cone and center location of workpiece, which are as follows: D= 206.4mm, θ=30°, φ=75°, (C_x, C_y, C_z)=(0,-103mm,93mm), H_t=20mm, and H_b=30mm. Values of feedrate and tool radius are used as same as those in first case study but spindle speed of 5000min^{-1}. Figure 1.5 compares simulated and measured machining error trajectories with respect to nominal surface of the taper cone. In this case, simulated results are also found to have a good match with measured ones. Further, a comparison of simulated and measured circularity errors for both case studies is summarized in Table 1.2.

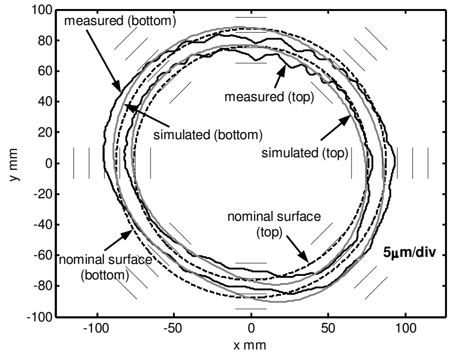

Figure 1.4. Simulated and measured machining error trajectories of the machined cone for case study I

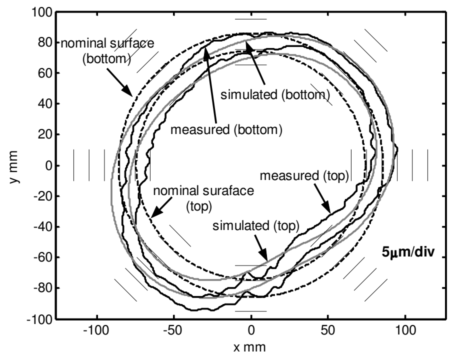

Figure 1.5. Simulated and measured machining error trajectories of the machined cone for case study II

Table 1.2. Summary of circularity errors for both case studies

Circularity errors	Case study I		Case study II	
	Simulated	Measured	Simulated	Measured
Bottom (μm)	7.2	9.4	13.3	17.3
Top (μm)	6.7	8.8	13.0	19.5

1.5.2 Error Compensation

With an aim to improve machining accuracy, an error compensation for tool position and orientation is carried out. First, an erroneous tool path due to kinematic errors is calculated. Error values in tool position and orientation between erroneous and nominal tool paths are obtained. Then, a compensated tool path is calculated by simply canceling error values of tool position and orientation from its nominal tool path. In this work, the presented error compensation is demonstrated for the case study II. Cutting test for error compensation is carried out using the same machining condition in case study II. Figure 1.6 shows compensated machined surface trajectories obtained from experiments. Compared to Fig.1.5, it is found that, error compensation, circularity errors are reduced from 17.3μm to 10.1μm at bottom and 19.5μm to 11μm at top surfaces of the machined taper cone, and hence machining accuracy is improved significantly.

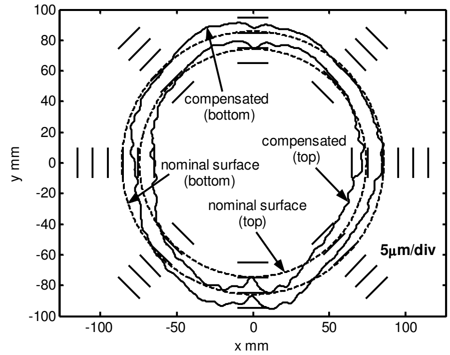

Figure 1.6. Compensated machining error trajectories of the machined cone for case study II

1.6 Conclusion

In this paper, machining accuracy of a 5-axis machine tool with kinematic errors is predicted and evaluated. By using an error model with kinematic errors, machining errors on a standard tilted taper cone (NAS979) workpiece is simulated. Case studies with cutting experiments on a target 5-axis machine tool verify the effectiveness of prediction of machining accuracy in 5-axis machining. An error compensation for tool position and orientation is demonstrated. Experiments for error compensation show a significant improvement in machining accuracy in terms of reduction of circularity errors of the machined surface.

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