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3D circular interpolation motion equivalent to cone-frustum cutting in five-axis machining centers and its sensitivity analysis

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Abstract

The present paper describes a testing method for five-axis machining centers using three-dimensional circular interpolation movement equivalent to cone-frustum cutting. In the present paper, the test conditions, such as the half apex angle of cone-frustum and the sensitive directions of the ball bar device were investigated. In addition, the sensitivity coefficient of each axis was investigated. It is found from the analysis of the sensitivity coefficient that the trajectory due to the errors of the axis of rotation is strongly affected by the sensitive direction of the ball bar for the case of a half apex angle of 45°.

Keywords: Standardization; Measurement; Ball bar; Sensitivity coefficient;

1. Introduction

A measuring method using a telescoping ball bar was proposed as an alternative to the machining test [1-3]. ISO/TC39/SC2/WG3 has decided to prescribe a method using the ball bar in ISO/DIS 10791-6[4]. One of the test codes prescribed in the draft standard is to check the simultaneous five-axis motion equivalent to the cone-frustum cutting by means of the ball bar. According to the test code, the measurement has to be conducted under two test conditions, namely, half apex angles of 15° and 45°. Moreover, the WG3 has prescribed the test condition such that the ball bar axis is set to be perpendicular to the conical surface of the cone-frustum.

When the center position of cone-frustum is located far from the centerline of the rotary table, the moving ranges of the Y, Z and A axes increase, and also the reversal positions of all of the axes appear independently [5]. However, neither the difference in the trajectories measured under half apex angles of 15° and 45° nor the sensitive direction of the ball bar has been investigated.

Thus, the detailed model of the pitch error of the axes of rotation is newly introduced to a previously developed simulation model [6-7]. The 3D circular interpolation movement equivalent to cone-frustum cutting is simulated, and the validity of the simulation model is clarified through comparison with the measurement data. The influence of the backlash and pitch error of two axes of rotation is investigated using the simulation model. In addition, the sensitivity coefficient of each axis is investigated.

2. Ball bar measurement and simulation

2.1. Ball bar measurement

Figure 1 shows the setup of the virtual cone-frustum and the ball bar. The symbols are defined as shown in the figure. The relative displacement between the center of the ball $O_T(X_T, Y_T, Z_T)$ of the table side and the center of the ball $O_S(X_S, Y_S, Z_S)$ mounted on the spindle nose is measured. Figure 1(a) shows the sensitive direction of the ball bar that is set to be perpendicular to the conical surface of the cone-frustum (perpendicular measuring method). Figure 1(b) shows the sensitive direction of the ball bar is parallel to the cone-frustum bottom (parallel measuring method).
The measurement and simulation are conducted for half

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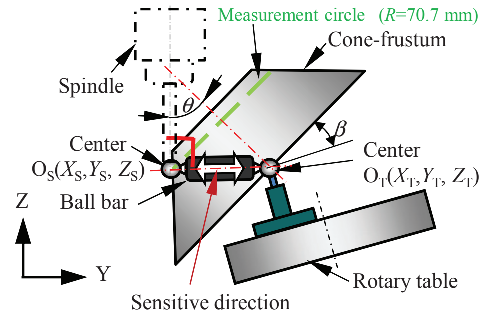
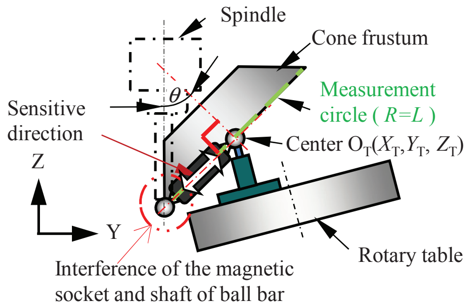
apex angles of θ=15° and 45° using two measuring methods defined in Fig. 1, and the inclinations of the cone-frustum are β=10° and 30°, respectively.



(a) Perpendicular measuring method



(b) Parallel measuring method

Figure.1: Two measuring methods of conical movement by means of ball bar (θ: half apex angle, and L: ball bar length 100 mm)

2.2. Simulation model

Figure 2 shows block diagrams of the linear and rotary axes of the feed drive system of the five-axis MC used in the experiment [6-7]. The linear axes are driven by an AC servo motor through a ball screw, and the axes of rotation are driven by a worm gear having reduction ratio R. Friction torque F is introduced to the linear axes as a disturbance, and the backlash and pitch error of the axes of rotation are also introduced into the axes of rotation.

2.3. Pitch error model of the axes of rotation

In the present study, the model of the pitch errors of axes of rotation was developed to precisely simulate the trajectory. The pitch error of an axis of rotation can be measured by a ball bar device in the tangential direction of the axis of rotation, as reported previously [8]. The pitch error of the axis of rotation was measured by simultaneously controlling the X, Y, and C axes and the Y, Z, and A axes. The obtained data was analysed by fast Fourier transform (FFT). The pitch errors of higher-order components that appeared in the trajectory of three axis control movement were modelled as follows:

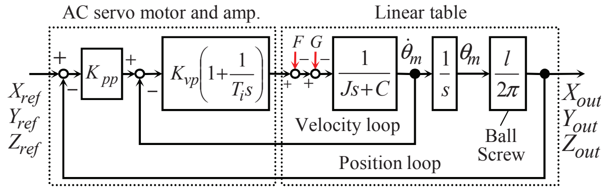
$$R = R_{all} + \sum_{i=1}^{n} W_i \sin(N_i R_{all} \theta_m + \phi_i) \qquad (1)$$

where, R_{all} is the reduction ratio of the worm gear, θ_m is the motor rotational angle, W_i is the amplitude of the ith pitch error, N_i is the number of peaks per rotation of the ith pitch error, and ϕ_i is the phase of the ith pitch errors. In order to sufficiently express the error of a real machine, the parameters of Eq. (1) were determined so as to fit, to the highest degree possible, the pitch error curve of a real machine.

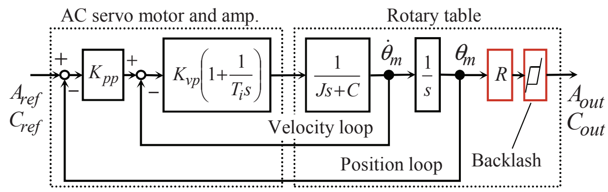
Figure 3 shows the amplitude spectrum of the pitch error of the A axis. The figure shows that the components are equal to the integral multiple of the number of teeth of the worm wheel and the other components exist in the pitch error components of the A axis. All of the parameters including the pitch error of the C-axis were identified based on the results shown in Fig. 3.

3. Validity of the simulation results

3.1. Influence of the center position of the cone-frustum for a half apex angle of 15°



(a) Block diagram of linear axes (G: Z-axis only)



(b) Block diagram of axes of rotation

K_{pp} is the positional loop proportion gain, K_{vp} is the velocity loop proportion gain, and T_i is the velocity loop integration time. J is the total moment of inertia of the mechanism, C is the viscous damping factor, and l is the lead of the ball screw. Here, R is the reduction ratio of the worm gear used for the A and C axes.

Figure.2: Simulation models of linear and rotary axes

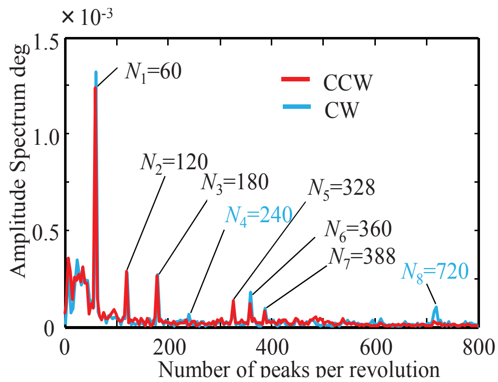


Figure 3: Amplitude spectrum of pitch error of A axis