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Study on Tool Path Generation Method for Reducing Energy Consumption of 5- axis NC Machine Tools

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Abstract
In recent years, many researchers in various fields have focused on the energy-saving technology. In a manufacturing field, the reduction of the power consumption has been also demanded. Thus, it has revealed that the power consumption of the motion of NC machine tools changes depending on the motion direction, the feed speed, and the acceleration parameters and so on. In other words, the energy consumption for the machining can be reduced by generating the tool path considering with the motion of the machine tool. In this study, the energy-saving tool path generation method for 5-axis machine tool was developed which considers to minimize the power consumption based on the form shaping theory. Then, the energy consumption of the motion in tool path generated by proposed method was estimated by the machining test.

Keywords: Energy consumption, NC machine tools, CAD/CAM, Form shaping theory

1. Introduction

In recent years, the energy-saving techniques, such as the near net shape manufacturing and the additive manufacturing technologies, made significant progress in industry. Furthermore, it is raising the awareness of "Smart Factory" since "Industry 4.0" is advocated. Thus, the use of energy-saving technique for NC machine tools is important in manufacturing fields.

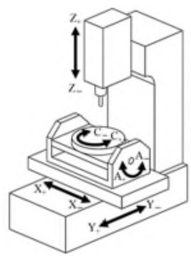
In addition, the demand for products with complicated shapes is increasing, and it has necessitated of generation a tool path by using CAM software. Recently, CAM software can be used to get high accuracy and interference avoidance. However, in such CAM software, the tool path is generated without considering the motion of the feed drive axis of NC machine tools. Therefore, tool paths cannot be generated with energy-saving taken into consideration. Thus, the tool path generation method considering with the motion of each axis on machine tool has been proposed in our previous research[1].

In this study, an algorithm of tool path generation with energy-saving was developed focused on the power consumption of the feed drive axis of a 5-axis machine tool. This algorism is based on the form-shaping theory which can express the form-shaping motion of the machine tool by the tool position vector in the work coordinate system.

2. Measurement of power consumption

Figure 1 shows the schematic diagram of a 5-axis machining center used. The measurement tests of the power consumption for each linear and rotational axis during reciprocating motion was carried out. The feed rate was set to be 250, 500, 750, 1000 mm/min (degree/min) and the distance of 90mm and 90 degree. The average power consumption of each linear and rotational axis are listed.

In this case, the power consumption of rortational axes increases with feed rate. On the otherhand, the power consumption of linear axes does not change greatly depends on feed rate. In addition, In X and Y-axis, the average power consumption of the motion to positive and negative displacements are nearly equal. In contrast, it can be seen that the power consumption of Z-axis driven to the positive direction is much larger than that driven to the negative direction. The power consumption strongly depends on the direction of the motion, it can be said that the power consumption of the Z-axis is greatly influenced by gravity.



Quantity symbol		Average power consumption *W*/ (J/s)	
P_{aX-}	P_{aX+}	33.87	34.55
P_{aY-}	P_{aY+}	68.07	65.57
P_{aZ-}	P_{aZ+}	427.8	612.1
P_{aA-}	P_{aA+}	$5.736\times10^{-2}v$	$8.483\times10^{-2}v$
P_{aC-}	P_{aC+}	$3.231\times10^{-2}v$	$3.093\times10^{-2}v$

Figure 1. Schematic diagram of 5-axis machining center and power consumption for each axis motion

Therefore, the energy consumption of each axis motors at each tool attitude along the curved surface can be calculated from at each point and the linear and rotational axis energy consumption per unit time W_{dL} and W_{dR} (average power consumption) as Eq.(1).

$$W_{dL,dR} = \frac{P_{a(X,Y,Z)\pm,a(A,C)\pm}}{v}\times 60 \quad (1)$$

3. Form shaping theory

The form-shaping motion of the machine tool is expressed by the relation of the tool position vector in the work coordinate system. This relationship can be obtained from the coordinate transformation of the form-shaping chain of the machine tool. In addition, the translational and rotational motion for each axis can be represented by the homogeneous coordinate transformation matrices *A* as Eq. (2).

$$A = A^6 A^4 A^1 A^2 A^3 \quad (2)$$

In this case study a machine tool as shown in Fig. 1 with a mechanism code of K = 640123 was considered. From the coordinate transformation matrix of Eq. (2), the position vector from work coordinate origin to tool origin C is expressed as Eq.(3).

$$\boldsymbol{C} = A\begin{bmatrix}0 & 0 & 0 & 1\end{bmatrix}^T \tag{3}$$

$$\begin{bmatrix} r_x \\ r_y \\ r_z \\ 1 \end{bmatrix} = \begin{bmatrix} x\cos\theta - y\cos\varphi\sin\theta + z\sin\varphi\sin\theta \\ x\sin\theta + y\cos\varphi\cos\theta + z\sin\varphi\cos\theta \\ y\sin\varphi + z\cos\varphi \\ 1 \end{bmatrix} \tag{4}$$

In general, because the tool position vector is expressed in three dimensions as [x y z], the first three components of Eqns. (3) and (4) represent 3D position vectors. Additionally, the position vector is an eigenvector whose fourth component is 1.

Therefore, solving the first three components of Eq. (4) are for x, y, and z yields

$$\begin{cases} x = r_x\cos\theta + r_y\sin\theta \\ y = -r_x\cos\varphi\sin\theta + r_y\cos\varphi\cos\theta + r_z\sin\varphi \\ z = r_x\sin\varphi\sin\theta - r_y\sin\varphi\cos\theta + r_z\cos\varphi \end{cases} \tag{5}$$

The components of tool position vector r_x, r_y, r_z are set to be constants, and x, y, and z can be expressed as function of φ and ϑ. Thus, the displacements of linear axis direction x, y, and z indicated for a machine tool can be calculated by Eq. (5). As the results, linear axial displacement along a parameterized curved surface S_L is described as shown in Fig. 2 [2].

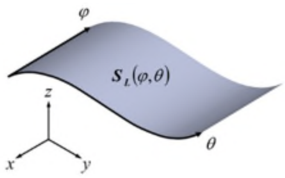


Figure 2. Linear axial displacement on a parameterized curved surface

By using the axis displacement curved surface S_L, it is possible to generate a tool path in consideration of the displacement of the feed drive axis based on representing the movement of the rectilinear axis in the rotating coordinate system. However, this method has not consider about the power consumption. Thus, the energy consumption calculated by multiplying the displacement of each axis and the average power consumption is expressed in S_L curved surface. Then, the power consumption curved surface S_{WL}, S_{WR} are defined by Eqns.(6) and (7). Therefore, the total power consumption is defined as Eq.(8).

$$S_{WL} = W_{dX}\cdot x + W_{dY}\cdot y + W_{dZ}\cdot z \tag{6}$$

$$S_{WR} = W_{dA}\cdot\varphi + W_{dC}\cdot\theta \tag{7}$$

$$S_W = S_{WL} + S_{WR} \tag{8}$$

Based on Eq. (8), the linear axis power consumption curved surface S_W is expressed as Fig.3.

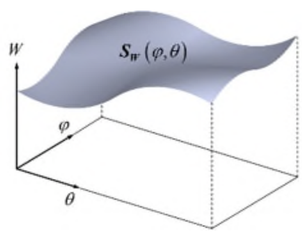


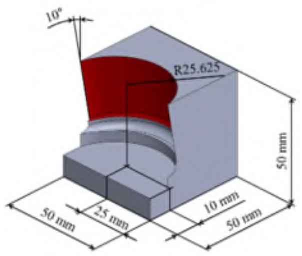
Figure 3. Axis power consumption on a curved surface S_W

4. Case study

In order to verify the proposed tool path generation method, we carried out the machining test, which is finish machining process using the ball end mill to the overhung surface product.

Figure 4 shows the product shape which has overhung surface and each dimension for machining test. The cutter location was generated with contour lines, and the tool posture at that cutter location was calculated so that the power consumption was minimized based on proposed method.

Then, the measurement test of the energy consumption were also carried out, and it is revealed the difference between the tool path by the proposed method and by the conventional CAM software. Figure 5 shows the results of the average power consumption for the motion of each axis and total during machining tests. It can be seen that the energy consumption has been reduced compared to commercial CAM software, because the tool path generated by proposed method can suppress the motion of Z-axis which consumes the power larger than other axis. This tool path is generated by using rotational axes which have lower power consumption. In this case study, the total energy consumption has been reduced by 69 percent.



Cutting condition	
Relative feed of workpiece and tool	200 mm/min
Pick feed	1 mm
Workpiece	SB0470
Tool	R3 ball endmill

Figure 4. Machining shape for case study

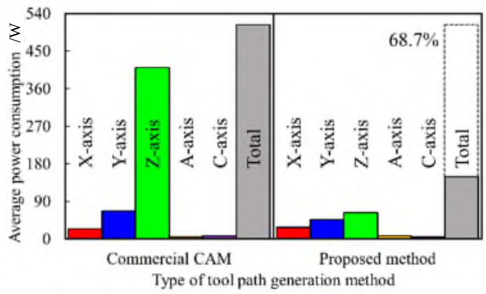


Figure 5. Measurement results of average power consumption for motion of each axis during machining test

5. Conclusion

In this study, a tool path generation method was proposed. This method consideres with the energy consumption based on the motion of the feed drive axis which can be derived from the form shaping theory. Then, the machining test was carried out based on the tool path generated by the proposed method. As the results, it is confirmed that the proposed tool path generation method can generate the tool path considering with both of the tool posture and the energy consumption of the motion of axes in 5-axis machining center.

Finally, the measurement test of the energy consumption were carried out, and it demonstrated that the proposed method can generate a tool path which is possible to reduce the energy consumption than that by the conventional CAM software.

References

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