Motion Path Evaluation based on Energy Consumption of Feed Drive System in NC Machine Tool

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Abstract:
NC machine tools generate desired shapes by relative motion control between tool and workpiece. Since several tool paths exist in machining products with NC machine tools, it is difficult to plan the suitable motion path for the machining. This study investigates the energy consumption of feed drive systems of NC machine tools during the machining operation. In this study, an evaluation method to predict the energy consumption for a given motion path patterns is proposed. The results of this study confirmed that the proposed method can evaluate the power efficiency of each motion path based on its energy consumption.

Keywords: energy consumption, motion path, NC machine tool, feed drive system, CAD/CAM

1. Introduction
The requirement from consumer for making products has been changing from functionality to comfortableness. Thus, the importance of the NC machine tool which can perform complicated machining operation increases more and more. In addition, the demand to the improvement of the productivity and high precision of the products is increasing in the manufacturing field. Therefore, the tool path pattern has been complicated and various.

Since several motion of tool paths exist in machining products with NC machine tools such as the machining center, it is difficult to plan a suitable motion path for machining. In the conventional CAM system, the motion path is selected by a CAM operator and the system only manage the geometric information of the desired shape. This fact means that the generated motion path is not suitable for the NC machine tools which have different specifications. Therefore, many researchers have studied about the motion path generation for a complicated cutting process to achieve high accuracy and efficiency in the minimum processing time.[1-4]

On the other hand, in recent years, reduction of the energy consumption of NC machine tool is greatly demanded in manufacturing field. Thus, many researches have been investigated the energy consumption of NC machine tool during a cutting process.[5-10] Nancy and others explained the energy consumption changes in cutting process suggested of a specific form[5]. Rangarajan et al. selected the efficient tool path for face milling by changing the setup position of a work piece[6]. In addition, authors have been clarified that the power consumption of feed drive system in NC machine tool changes by applying different motion path, moving direction and feed rate[10]. From these results, the energy consumption required for a cutting process can be reduced by devising motion paths. This study investigates the energy consumption of feed drive systems of NC machining tools during the machining operation. This study proposes an evaluation method to predict the energy consumption for the given motion path pattern. It is assumed that the motion path pattern can be evaluated based on the energy consumption per 1mm moving distance. As the results, it is shown that the proposed estimation index can evaluate the energy consumption based on the difference in feed rate and the tool path pattern.

2. Measurement method
In this study, in order to clarify the energy consumption of each feed motions, the electric power consumption of feed drive system of the 5-axis machining center is measured. This 5-axis vertical type machining center consists of X-, Y-, Z-, B- and C-axis. Figure 1 shows the structural configuration of the 5-axis machining center used in this study.

In order to measure the power consumption of the feed drive system, the electric current and voltage are measured on the link bars which connect servo amplifiers and a converter. Figure 2 describes measurement points. The electric current is measured by using a clamp type meter and the electric voltage is measured by using a differential probe. Both of the current and voltage are recorded by a data logger. The current and voltage are converted into RMS value based on Eqs. (1) and (2). T is integration time and it is set to 1ms. The electric power is calculated from the RMS values by using Eq. (3).

The electric power is consumed by the peripheral components and the NC even if the feed drive system idles, the electric power is set to 0 W when all the feed drive motors and the spindle motor are stopping.

\[ I_{rms} = \sqrt{\frac{1}{T} \int_0^T (i(t))^2 \, dt} \]  \hspace{1cm} (1)

\[ V_{rms} = \sqrt{\frac{1}{T} \int_0^T (v(t))^2 \, dt} \]  \hspace{1cm} (2)

\[ P = I_{rms} \times V_{rms} \]  \hspace{1cm} (3)
3. Evaluation index based on the energy consumption

This study proposes the evaluation index for tool paths based on its energy consumption. In order to determine the index, a measurement tests of the power consumption are carried out at eight different feed rate (500, 1000, 1500, 2000, 3000, 4000, 5000, 6000 mm/min) during a linear reciprocal motion of 200 mm moving distance. The dwell time of 2 s takes between going and coming motions. The schematic view of the motion pattern is shown in Fig. 3. Measurement tests are carried out by moving each linear axis (X-, Y-, and Z-axis) separately. In addition, the motor torque of each axis is recorded at the same time. From these results, the energy consumption per 1 mm moving distance at each feed rate is calculated. Moreover, the average of motor torque is calculated. Figure 4 shows the measured results of a X- axis motion with feed rate of 3000 mm/min. Figure 4 (a), (b), and (c) show the velocity, the motor torque, and the power consumption, respectively.

The energy consumption of each movement 1 mm is calculated from average power consumption during a constant motion velocity. In order to eliminate the transient data, the data at the start and the end of motion for 0.5 s are ignored. The average of the power consumption in each direction is calculated by dividing by the feed rate. The average power consumption of the positive movement direction is noted as $P_+\ [W]$, the negative movement direction is noted as $P_-\ [W]$. The energy consumption of each 1 mm movement distance ($J_{1\text{mm}}$) is expressed in Eq. (4). In this equation, $V$ is the feed rate.

$$J_{1\text{mm}} = \left( \frac{P_+}{V} + \frac{P_-}{V} \right) / 2 \quad (4)$$

In addition, the measured result of a Z- axis motion with feed rate of 3000 mm/min is shown in Fig. 5. From this result, the power consumption of a Z- axis changed by a motion direction.

Figure 6 shows the energy consumption per 1 mm and torque at each velocity. Figure 6 (a) and (b) show the results of X-axis and Y-axis, respectively. From these results, both of the energy consumption and the motor torque of Y-axis are larger than one of X-axis. Because
Y-axis is driven by two feed motors and the driven mass is larger than X-axis. In addition, the motor torque is monotonically increasing at over 1000 mm/min. On the other hand, the energy consumption per 1 mm moving distance is the smallest at 3000 mm/min.

Moreover, the measurement test on Z-axis is also carried out. The energy consumption per 1 mm movement and the average motor torque are also calculated. The calculation results show that the movement direction has influenced the Z-axis which is influenced by the gravity. Thus, they are calculated separately by the moving direction. The measurement results of Z-axis are shown in Fig. 7.

According to these results, in upward motion, the energy consumption per 1 mm moving distance of Z-axis decreases monotonically when the feed rate of increase. In downward motion, it increases with the feed rate. In addition, the energy consumption in downward motion takes minus value. This fact means that the energy consumption in downward motion is smaller than one in the stop state. From Fig. 7 (b), the motor torque of Z-axis in upward motion is larger than the one in downward motion, because large torque is required by raising the spindle.

Based on the energy consumption per 1 mm movement of each axis, the energy consumption of the tool path is simulated. The energy consumption per 1 mm movement of each X-and Y-axis is \( J_{\text{1mmX}} \) [J/mm] and \( J_{\text{1mmY}} \) [J/mm]. The energy consumption of Z-axis in upward motion is \( J_{\text{1mmZ+}} \) [J/mm], while in downward motion is \( J_{\text{1mmZ-}} \) [J/mm]. The total movement distance of each axis is \( X \) [mm], \( Y \) [mm], \( Z_+ \) [mm], \( Z_- \) [mm]. The energy consumption \( J_{\text{est}} \) [J] is estimated shown as Eq. (5).

\[
J_{\text{est}} = J_{\text{1mmX}} X + J_{\text{1mmY}} Y + J_{\text{1mmZ+}} Z_+ + J_{\text{1mmZ-}} Z_- \quad (5)
\]

In addition, it is clarified that the power consumption of Z-axis during stop is different by the motion direction before it stops \([10]\). It can be also seen in Fig.5. The difference of the power consumption after plus direction motion and the power consumption after minus direction motion is set to \( J_{\text{X+stop}} \). In consideration of this, the energy consumption of the tool path movement on X-axis or Y-axis after the motion on Z-axis in plus direction motion is simulated as shown in Eq. (2).

\[
J_{\text{totX+stop}} = (J_{\text{X+stop}} + J_{\text{1mmX}}) X + (J_{\text{Y+stop}} + J_{\text{1mmY}}) Y \quad (6)
\]

4. Verification of evaluation index
In order to verify the validity of the proposed evaluation index, the measurement tests are carried out in various tool paths. The simulated result based on proposed evaluation index is compared with the measured results of the energy consumption in different eight path patterns. It is assumed that the ball end mill is swept on \( 50 \times 50 \) mm area of XY plane. The tool path patterns are described in Fig. 9. The Path 1 and 2 are simple linear scanning paths. The Path 3 and 4 have circular motion of 2.5 mm radius between scanning paths. The Path 5 is a spiral path pattern. The position commands of X- and Y-axis in specific path patterns at 3000 mm/min are shown in Fig. 9. The value on the right side Fig. 9 explains, respectively, (1) the tool travel distance, (2) the motion distance of X-axis, (3) the motion distance of Y-axis, (4) the total X- and Y-axis moving distance, (5) the required motion time. According to Fig. 9, the tool Path 5
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Fig. 8 Tool path patterns for X- and Y-axis motion

Fig. 9 Motion of X- and Y-axis test tool path patterns

has the shortest tool travel distance and the total required motion time. On the other hand, the tool Path 3 has the longest required motion time.

Figure 10 shows estimation results of the energy consumption for each tool path pattern. Figure 10 (a) shows the measured results and Fig. 10 (b) shows the predicted results. From these results, the measured result of the energy consumption at 3000 mm/min has the smallest value among other tool path patterns. In the estimated results, the energy consumption at 3000 mm/min also has the smallest value. These result means that the proposed estimation index can evaluate the difference of the energy consumption by the feed rate. On the other hand, the energy consumption of Path 1 has the smallest among other tool path patterns in any feed rate. Therefore, it is also can be inferred that the proposed estimation index can evaluate the difference of the energy consumption for a given tool path pattern. Furthermore, by comparing Path 1 and Path 2 and Path 6, the energy of Path 1 is the smallest in three paths although the total travel distance and time between them are same. This reason is that the travel distance of Y-axis in Path 1 is the smallest because the power consumption of Y-axis is larger than X-axis. Moreover, Path 5 consumes the largest energy. Although Path 5 has the shortest the motion time, the total of X- and Y-axis moving distance is the longest. From this result, it seems that the energy consumption becomes larger if the total moving distance in each axis is growing longer.

The additional measurement tests of the tool path patterns including Z-axis motion are carried out. Figure 11 shows the tool path patterns. The difference between Path 7 and Path 8 is total moving distance of X- and Y-axis. Figure 12 shows the power consumption of the motion at 3000 mm/min. According to this result, the power consumption of the motion after Z-axis upward motion is...
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Energy consumption

Fig. 15 Comparison of measurement and estimated energy consumption

(a) Tool path A

(b) Tool path B

(c) Tool path C

Fig. 14 Generated tool paths by CAM for machining of the hemisphere

5. Tool path evaluation test

In order to verify the effectiveness of the proposed estimation index in practical machining operations, NC data of machining a hemisphere which has 20 mm radius was created by CAM. The workpiece size is $50 \times 50 \times 50$ mm. Figure 14 shows the three tool path patterns which are generated by CAM. In these cases, the step over is set to 1 mm. Tool path A consists of the one way scanning larger than one of the power consumption after Z-axis downward motion.

Figure 13 shows the measured results and estimated result of Path 7 and Path 8. It can be seen that the energy consumption becomes smaller at 3000 mm/min for both of measurement and estimated result. In addition, the energy consumption of Path 8 is larger than one of Path 7 at any feed rate. These results show that the proposed estimation index can estimate the energy consumption of any given tool path patterns in X-, Y-, and Z-axis motion.
line motion which has an escape height 25 mm along with the Z-axis. Tool path B consists of bidirectional scanning line motion along with the X-axis. Tool path C consists of a contour line motion which has 1 mm height interval.

The measured and estimated results for each tool path patterns A, B and C are shown in Fig. 14. It can be seen from these results, in Tool path B and C, the energy consumption at 3000 mm/min is the smallest. However, in Tool path A, the measured result of the energy consumption at 5000 mm/min is the smallest. On the other hand, the estimated result at 3000 mm/min feed rate is the smallest. This is considered that the measurement error is included.

From the measured results of the energy consumption for each tool path patterns, it can be clarified that the energy consumption of Tool path C is the smallest under 2000 mm/min, Tool path B is the smallest over 3000 mm/min. However, the estimated results show that the energy consumption of Tool path B is the smallest at any feed rate. These causes are maybe that this proposed method can not estimate the power consumption of Z-axis correctly, because the tool path A has the longest distance of Z-axis motion. Furthermore, it will be necessary to consider each axial velocity changes.

Based upon these results, these results have shown that the one way scanning line motion has the largest energy consumption, because the power consumption of the motion along with Z-axis has a big influence to the energy consumption during the machining operation.

6. Conclusions

This study investigates the energy consumption of the machining operation and proposes the estimation index to estimate the tool path based on the energy consumption of each axis. Conclusions can be summarized as follows;

1) The proposed evaluation index can evaluate the energy consumption of tool path patterns in different feed rate.
2) The difference in the energy consumption of each different tool path patterns can be evaluated by using the proposed evaluation index
3) The energy consumption will become larger if the total moving distance is growing longer.
4) The practical tool paths patterns in machining a hemisphere has verified the validity of the evaluation index

This study proposes an evaluation method of tool path patterns. It is expected that the proposed method can be applied to design the optimum tool path pattern which consumes less energy.

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