Evaluation and Improvement of Productivity for Machining Centers

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学位論文要旨

Summary The productivity of a machining center is influenced directly by the quality of NC programs. However, as the cutting speed increases, numerous "tiny" NC blocks exist in NC programs, resulting in much lower feedrate than the commanded one. Therefore, no conventional software, if any, applies anymore. To evaluate and improve the productivity, an effective feedrate factor and factor of productivity evaluation are proposed, and it has been found that in high-speed cutting the two factors depend on a kinematic factor expressed as a function of command feed rate, average per-block travel and moving vectorial variation of the tool and ac/deceleration or time constants. Based on these, an NC program simulator was developed. With it, the cutting time can be calculated accurately even in high-speed cutting, and the cutting parameters, such as depths of cut, material removal rate (MRR), feed rate, tool path pattern and machining feature can be extracted from NC programs. Implementing it, three actual NC programs used in high-speed cutting have been analyzed, and case-dependant improvements on the productivity are suggested. In addition, effects of tool path patterns and tool types and diameters for typical machining features on productivity have been investigated with *I-DEAS* CAM tool and the simulator, and the geometric error caused by tool path disturbance in high-speed cutting has been analyzed quantitatively and its compensation and reduction are suggested. Finally, based on the evaluated productivity and extracted cutting parameters, algorithms for optimizing NC programs are developed on conditions of maximum MRR and cutting power.

1. INTRODUCTION

The productivity of the machining center depends heavily and directly on the quality of NC programs. Conventionally every effort has been made to improve the productivity by increasing feedrates. That has worked well in conventional machining. However, recent study shows that the estimation of the machining time only based on the commands differs from the actual value and it is hardly improved just by feedrates in most cases of high-speed machining. Other major factors have to be considered. This dissertation just serves for this purpose.

In this study, the factors and their relations have been found. Taking these factors into consideration, an NC program simulator was developed to analyze and optimize NC programs. With this simulator, the productivity can be evaluated accurately, and the cutting parameters such as depths of cut, material removal rate (MRR), tool path pattern and machining feature can be extracted. Finally, based on the evaluated productivity and extracted cutting parameters, NC programs are optimized on conditions of maximum MRR and cutting power. The overall block diagram of the system is shown in Fig.1.

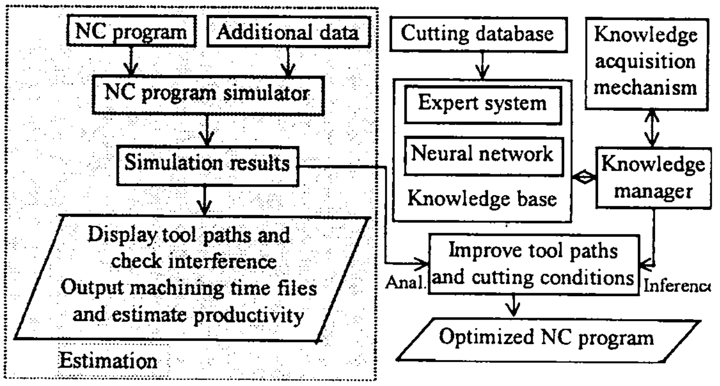


Fig.1 Overall block diagram of the system

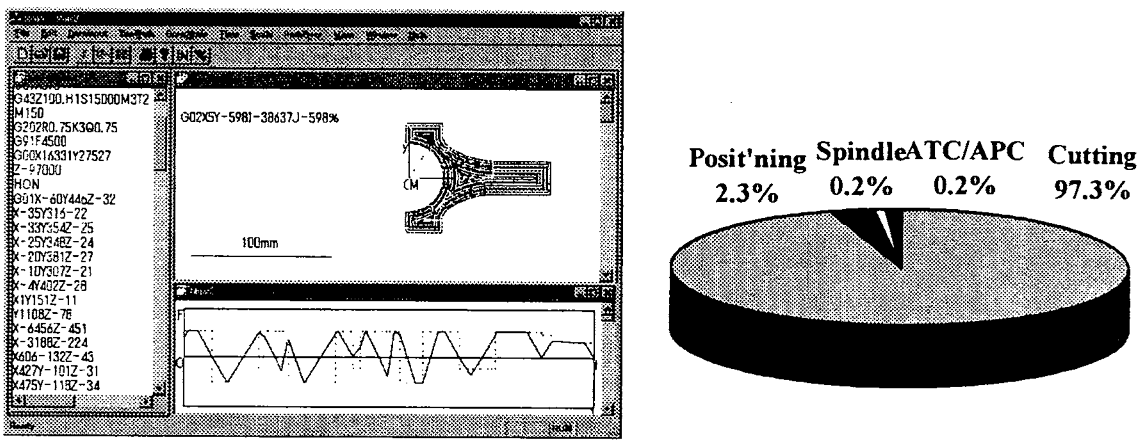
2. NC PROGRAM SIMULATOR

2.1 Development of NC Program Simulator

The NC program simulator was developed in Visual C++ under Windows 95. It has the following functions: calculation of machining time, evaluation of productivity and extraction of cutting parameters. The NC codes that can be analyzed by the simulator include M98 (sub-program), G65 and G66 (macro), and optional codes, besides such basic codes as G00-G03. The tool paths are drawn and the instantaneous feedrates are shown on the screen when each block is analyzed while the productivity is estimated.

2.2 Analysis of an NC Program by the Simulator

A sample NC program, *Conrod*, was analyzed. It is used to cut a forging mold, and it has 40,240 blocks including the optional codes for specifying accelerations and feedrate limit. End-mills are used and changed four times. Fig. 2 shows the analysis results of tool paths, instantaneous feedrates and ratios of various machining times.



(a) Tool path and instantaneous feedrate **(b) Ratios of machining time**

Fig.2 Analyzed results of *Conrod* NC program

3. EVALUATION OF PRODUCTIVITY

3.1 Calculation of Machining Time

The machining time for a workpiece includes the cutting (feed) time, positioning (feed) time, ac/deceleration time of the spindle and ATC/APC time, *etc*. The cutting time is calculated in two feed functions: exponential and linear.

Exponential feed function. From the block diagram of the CNC controller, the cutting (feed) time in an NC block is estimated as

$$t = (d + (T_1 + T_2)(2F - f_S - f_D)) / F \quad (t >> T_1) \tag{1}$$

where d is the moving distance in the current block; f_S, f_D are the initial and final feedrates in the block respectively; F is the commanded feedrate or its limit, and T_1, T_2 are the time constants of the ac/deceleration and positioning system respectively.

Linear feed function. In the high-speed and high-precision machining mode, the feedrate in a linear function is applied. The relations of the feedrate and time can be divided into three cases shown in Fig.3. Suppose the feedrate at time t in the current block is denoted by $f(t)$ and the command feedrate in the next block F_1.

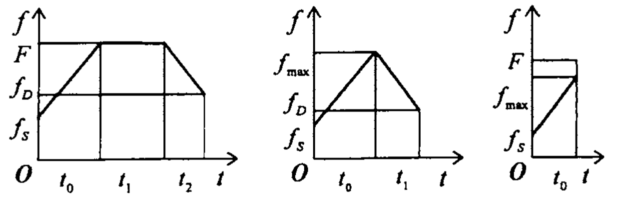


Fig.3 Feedrates in linear function

Case a: There exists time t where $f(t) = F$ (See Fig.3(a))

When $d' = (F^2 - f_S{}^2)/2a_0 + (F^2 - f_D{}^2)/2a_1 < d$ is satisfied, the cutting time is calculated by

$$t = (F - f_S)/a_0 + (F - f_D)/a_1 + (d - d')/F \tag{2}$$

where a_0, a_1 are the initial and final feed ac/deceleration of the current block respectively.

Case b: There does not exist t where $f(t) = F$ but $f_D = F_1$ exists (See Fig.3(b))

$$t = |f_{max} - f_S|/a_0 + |f_{max} - f_D|/a_1 \tag{3}$$

where $f_{max} = ((f_S^2 + f_D^2 a_0/a_1 \pm 2a_0 d)/(1 + a_0/a_1))^{1/2}$

Case c: There does not exist t where $f(t) = F$ and $f_D = F_1$ does not exist either (Fig.3(c))

$$t = |f_D - f_S|/a_0 \tag{4}$$

In the case of Fig.3(c), when the current block is the last of the consecutive moving blocks, the cutting time of the block should be compensated by

$$\Delta t = \sum \mathrm{d}t = f_D/a_0 \tag{5}$$

3.2 Factors for Evaluation of Productivity

Effective feedrate factor and kinematic factor. In the high-speed machining mode, it is accurate to use the actual average feedrate or effective feedrate factor instead of the commanded feedrate to evaluate the productivity. The factor is defined as the ratio of the actual average feedrate to the commanded one,

$$e = f_{av}/F \tag{6}$$

In the case of linear feed, from Eqs. (2) and (3), the effective feedrate factor is calculated as

$$e = \begin{cases} 1/(1+k), & 0 \le k < 1 \\ 1/(2\sqrt{k}), & 1 \le k \end{cases} \tag{7}$$

$$k = F^2 / ad_{av} \tag{8}$$

where k is called the kinematic factor in linear feed. Equation (7) shows that the smaller the factor k, the higher the average feedrate is.

Factor of productivity evaluation. Extending the definition (6) to the general case of multi-F code commands, the factor of productivity evaluation is defined which is the ratio of the command-based cutting time to the actual cutting time,

$$e = \frac{\sum t_i}{\sum t_i / e_i} = \frac{\sum d_i / F_i}{\sum d_i / F_i e_i} = \sum_{i=1}^{m} \left(\frac{1}{F_i} \sum_{j=1}^{n_i} d_{ij}\right) \Big/ \sum_{i=1}^{m} \left(\frac{1}{F_i} \sum_{j=1}^{n_i} \frac{d_{ij}}{e_{ij}}\right) \tag{9}$$

where d_i, e_i, F_i are the moving distance, effective feedrate factor and command feedrate in the i-th machining operation or throughout all the NC blocks of the i-th F command, respectively, d_{ij}, e_{ij} are the moving distance or travel and effective feedrate factor of the j-th NC block in the i-th operation.

In the case of the exponential feed, the effective feedrate factor of the i-th operation is approximated by

$$e_i = 1/(1 + k_i) \tag{10}$$

$$k_i = (T_1 + T_2) F_i \left(1 - \sum_{j=1}^{n_i} \cos\alpha_{ij} / n_i\right) \Big/ d_{av,i} \tag{11}$$

where n_i is the number of the moving NC blocks in the i-th operation, α_{ij} is the angle between the moving vectors of the (j-1)th and j-th blocks, and $d_{av,i}$ is the average per-block moving distance in the i-th operation.

$\sum_{j=1}^{n_i} \cos\alpha_{ij} / n_i$ is called the moving vectorial variation.

k_i is related to the command feedrate, moving vectorial variation of the tool, average moving distance and time constants. It is defined as the kinematic factor in exponential feed.

Analysis of the factors of productivity evaluation. In order to improve the productivity, it is desirable that the kinematic factor approximates to 0. Therefore, the cutting feed acceleration (or reciprocal of time constants) and the average feed distance should be increased as much as possible rather than the command feedrate, and the moving vectorial variation of the tool should be approximated to 1. The latter implies that the curvature of tool paths should be as small as possible.

3.3 Evaluation of Actual NC Machining Productivity

Estimation of machining time. Three NC programs of actual machining were analyzed with the NC program simulator. The results show that the analyzed machining time well agrees with the actual time with an error of less than 3%, and that the actual average feedrate is much lower than the commanded one, when the commanded feedrate is higher and the average feed distance is shorter. Besides, it is shown that when $k > 1$, e is only 55% or less, and when $k < 1$, e is larger than 76%. That implies that only approximate half of the command feedrate is utilized when $k > 1$.

Effect of feedrate override on productivity. The analysis shows that in the conventional machining where $k \ll 1$, the cutting time is proportionally shortened by increasing the feedrate; however, in the high-speed machining, the cutting time is hardly shortened by increasing feedrate since k is larger.

Effect of cutting feed acceleration override on productivity. The analysis shows that increasing the cutting feed acceleration will contribute to the productivity since k becomes smaller.

Effect of positioning feedrate and acceleration override on productivity. Considering that the maximum feedrate of the current machining centers is high enough, the positioning feed time accounts for little of the total machining time. Therefore, increasing the positioning feedrate or acceleration will contribute little to the productivity.

3.4 Evaluation of Productivity of Tool Path

The productivity of tool path patterns, types and diameters of tools and depths of cut is investigated on feature-based workpiece models. In this study, the slope, spline surface, pocket with islands and plane with bosses are taken to be typical machining features and their NC programs are generated with *I-DEAS* CAM tool, as well as that of a workpiece of complex shape with those features in it and their productivity is evaluated with the NC program simulator. Two patterns of tool paths, namely zigzag and contour line patterns, and two types of tools, namely ball endmill and flat endmill are used. Furthermore, the productivity under the condition of constant power with tools of different diameters is compared.

It is concluded that:

(1) In slope milling, the cutting time with a ball endmill is shorter than with a flat endmill in all cases except that the inclination approximates to $0°$ or $90°$, under the conditions of the same cutting accuracy and the same radial depth of cut. Besides, the larger the diameter of the tool, the more efficient the ball endmill is, compared with the flat endmill.

(2) The factor of productivity evaluation in contour line tool path pattern is larger than that of zigzag pattern for the typical machining features.

(3) The cutting time is shorter in contour line tool path pattern than in zigzag pattern, except milling a wavy spline surface along the valley of the wave in zigzag pattern.

(4) From the viewpoint of cutting with constant power, the cutting time is shorter with a tool of smaller diameter at a medium feedrate or lower, except milling a pocket with islands.

4. EXTRACTION OF CUTTING PARAMETERS FROM NC PROGRAM

Cutting parameters such as the depth of cut, material removal rate (MRR), tool path and machining features are implied in NC programs. They represent the machining know-how if the NC programs are made by skilled workers. Autonomously extracting the parameters accelerates accumulation of the cutting database. Moeover, it lays the foundation for the optimization of NC programs.

In this chapter, for the commonly used 2.5- and 3-axis milling, algorithms are developed based on tool path simulation for extracting radial and axial depths of cut, MRR, tool path patterns and machining features from NC programs, workpiece model and tool geometry file. They are different from previous ones in that 3-dimensional calculation is simplified to that of 1-dimension, a huge memory is not required and the calculation is extremely fast.

5. OPTIMIZATION OF NC PROGRAM

Based on the extracted cutting parameters, strategies are developed to optimize NC programs, which is done by optimizing feedrates and tool path patterns on condition of the maximum MRR, maximum cutting power and intelligent cutting databases.

6. ANALYSIS OF GEOMETRIC ERROR OF TOOL PATH IN HIGH-SPEED CUTTING

As cutting speeds increase, bigger geometric errors are caused in the tool paths. In this chapter, the errors are analyzed corresponding to different ac/deceleration cases and feedrate patterns, and the optimization to minimize the errors is suggested. It is summarized that

The expressions of the actual tool path and its error have been derived. The path is a parabola and the error is proportional to F^2/a for the linear feed and proportional to FT for the exponential feed where F is command feedrate, a is the acceleration and T is the time constant. A compensation technique is suggested to minimize the error by optimizing the ratio of the feedrates of two adjacent blocks and the optimized ratio for adjacent blocks of identical moving lengths is the number of golden section.

7. CONCLUSIONS

This dissertation consists of two parts: evaluation and improvement of productivity for MCs.

In the first part, the influences of effective feedrate factor, kinematic factor and tool paths on productivity were studied quantitatively. The kinematic factor is expressed by the command feedrate, feed acceleration or time constants and average per-block travel and moving vectorial variations.

In the second part, the extraction of the cutting parameters including depths of cut, MRR, tool path pattern and machining feature from NC programs and optimization of the NC programs were studied.

An NC program simulator was developed for the above tasks.

As the research on the evaluation and optimization of NC programs is extended, high productive strategies of NC program generation will be provided in the development of new CAM tools.

学位論文審査結果の要旨

平成10年7月28日に第1回学位論文審査委員会を開催し，提出された学位論文及び関連資料を詳細に検討した。平成10年8月6日の口頭発表後，第2回審査委員会を開催し，慎重に協議の結果以下のとうり判定した。本研究は，製品の多様化，高機能化に伴って高速化，高精度化の要求が増大しているエンドミル加工を対象として，加工工程や加工用NCプログラムの最適化に必要な指針と考慮すべき問題点を明らかにしている。このために，まず現状のNCプログラムを精度良く解析するためのNCプログラムシミュレータを開発し，実用されているNCプログラムから加工時間を正確に求めている。また，有効送り速度比を定義し，加工時間短縮の効果がその係数の大小で判定できること，近年の高速加工においては送り速度指令を増加させただけでは期待どうりの加工時間の短縮が見込めないことを明らかにしている。さらにNCプログラム1ブロック当たりの工具移動距離をできるだけ大きくすることで加工時間が短縮できることも明らかにしている。次に，汎用のCAMで生成した種々のNCプログラムを前述のシミュレータで解析して，等動力という条件では大径工具よりも小径工具のほうが，一般的な加工形状ではジグザグの工具経路よりも等高線の工具経路の方が加工効率が上げられることを示している。このように本研究は学術的な解析をベースにして，実用的なNC加工の高速化，高精度化を実現する上できわめて有益な知見を与えるものであり，本論文は博士（工学）に値するものと判定する。