Title

Efficient Tool Paths and Part Orientation for Face Milling

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Abstract

High speed machining is pushing the limits of feeds and speeds. A different approach for high throughput is described here. The focus is on the maximum feed that can be obtained for a segment; the feed rate losses due to sharp changes in tool path are minimized. The interdependency of individual axis drive speeds for a tool path segment are analyzed. There exists an optimum work angle relative to the axes that reduces losses and increases allowable feeds for particular segments, saving valuable cycle time and balancing feed drive loads. Face milling and roughing steps of end milling are the most attractive application areas.

Keywords:
Planning, Face milling, Tool path

1 INTRODUCTION

High speed milling is characterized by a significant increase in conventional feed rates and cutting speeds. The move towards high speed milling is driven by two different needs; increased productivity and improved cutting performance due to reduced cutting forces arguably caused by change in cutting mechanism [1-3].

Choice of tool path is very critical for efficient application of the milling process. The tool path determines the axial depth of cut thereby controlling the maximum cutting force while machining. The length of the tool path controls the productivity by way of cycle time. The tool path direction along with direction of spindle rotation controls the chip removal direction. Dornfeld et al. have demonstrated the influence of tool path on edge quality as well [4].

Tool path is also highly constrained by the specific type of milling operation performed. The processes can be distinguished based on the number of surfaces generated due to the milling operation. Face milling is used to generate flat surfaces, with one critical direction perpendicular to the spindle axis. The tool path normally consists of linear and curvilinear segments.

Tool path generation is usually handled by computer aided manufacturing (CAM) systems. The standard schemes are to have zigzag and contour parallel tool paths. Face and slot milling tool paths are usually one pass milling while pocket milling tool paths are repeated in loops. Optimal tool paths have also been generated for controlling edge quality and have been successfully employed in face milling. Optimization of tool paths for reduction of forces, improving edge quality or reducing tool or part deflection generally increases the length of the path. Usually, tool paths are specified to be parallel or perpendicular to the machine tool axes if possible.

The most active research areas with respect to tool paths and machine controllers are generation of the interpolation points for any arbitrary curve by the controller using piecewise linear approximations or PH curves, Taylor approximations etc. [5] and reduction in contour error and improved feed performance by controller design [6-8]. High speed machining has also renewed the focus on machine tool design [9].

The following sections of the paper study the effect of the orientation of tool paths with respect to the machine tool feed drives to try to reduce the cycle time losses and balances the loads on the feed drives. A case study and experimental results demonstrate modest savings achieved by this theory. Towards the end of the paper there is a discussion on the application of this concept as part of an integrated solution for the machine tool controller.

2 PART ORIENTATION

This paper takes an atypical approach for reducing the cutting time and improving the machine performance. The orientation of the tool path and workpiece-setup is defined with respect to the feed drive axis. Figure 1 gives a simple illustration of the “orientation”. Any configuration can be characterized with respect to θ which is a relative parameter. The starting orientation can be determined arbitrarily, but it is generally straight forward for prismatic parts. Theoretical bounding boxes, the smallest rectangle completely enclosing the object, can otherwise be used to find the starting orientation for curved parts. An important point to note here is that the transformation of the tool path and workpiece ensures that the cutting process does not change with the orientation. The orientation change can be accomplished by rearranging the fixture or, more conveniently, with a modular fixturing system.

The orientation determines to a large extent the interpolation that is required for each of the drives to accomplish the tool path. Considering the case of a simple straight line segment of a tool path; if the line segment is oriented along the X axis, only the feed drive along the X axis is engaged. If the segment is oriented at any other angle, $0<\theta<90°$, both X and Y axis feed drives will be engaged to generate the tool path. This concept is used repeatedly to demonstrate the various ways in which the cycle time can be improved.

The effect of this transformation on the accuracy of the contour, though not quantified in this paper, is not very relevant since the loss of accuracy for the conditions for which we desire to apply this theory is not in the critical direction. Also, it is assumed that there is sufficient travel in the X and Y directions to accommodate the proposed transformation.

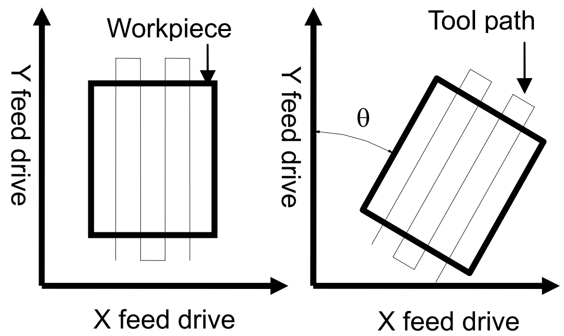


Figure 1: Orientation of tool paths.

3 EXPERIMENTAL SETUP

The experiments mentioned above and the case study were performed on a commercial milling machine with a standard controller. The tests were performed under a dry run setup and were timed using a stop watch. The resolution of the stop watch was 0.5s. For tests with multiple feeds and segments, the machine was warmed up using a canned routine and the experimental runs were performed in a random order to avoid any bias in the experimental results. The feed acceleration profile for this controller is given to be exponential. The time losses previously described were accounted for by ensuring that the program was looped for an equal number of times and an identical number of lines of code (LOC). The savings in time indicated in the charts are directly a measure of the savings obtained when everything else remains constant. The experiments were also repeated a multiple number of times, and at least 3, to ensure reproducibility.

4 CYCLETIME LOSSES

4.1 Toolpath design losses

Various elements contribute to the loss of time resulting in deviation from the feed rate and lengths specified in G code of the tool path program. This is particularly significant for high speed milling. These elements were characterized by running a series of tests. The tests were all run covering 15 m of total travel length with constant length segments going forward and reverse. Special tool paths, with triangle and square shaped geometry, were also timed for the same total length of travel. The length of the small indivisible segment, i.e. side of a triangle or square, segment going forward remained constant. Three primary sources of delay were observed:

1. Number of segments in the subroutine, which in turn is controlled by the segment lengths. Shorter segments take longer to machine the same workpiece again owing to the fact that the delay is moving from segment to segment. Figure 2 shows the time taken to machine for 15 m at 10m/min.
2. Number of times a loop is executed for a tool path subroutine. Let us assume that the square profile has to be machined 20 times. This can be achieved by writing 4 LOC, one line of code for each side of the square, for a square subroutine and looping it 20 times. The same objective can also be achieved by writing 8 lines of code, equivalent to machining the square twice with the subroutine and looping it 10 times. The second technique of machining reduces the buffer losses estimated between 15-20% of the total losses. This is explained in more detail in section 5.
3. Continuity losses in tool path segments. Figure 3 shows two tool paths of the same length and geometric entities, lines and arcs. At vertex **2**, corresponding to end of first segment and beginning of the second segment of toolpath in figure 3(a), the tangent flips. In case of figure 3(b), the tangent remains the same, possessing continuity. The angle through which the tangent changes is a measure of the continuity loss. Experiments showed that the difference in continuity can cause losses of up to 2% of total machining time or 10% of the savings. Geometrically continuous tool paths machine faster for the same lengths.

These losses can be overcome by effective NC programming for the tool path and proper choice of segment lengths during the early stages of tool path development

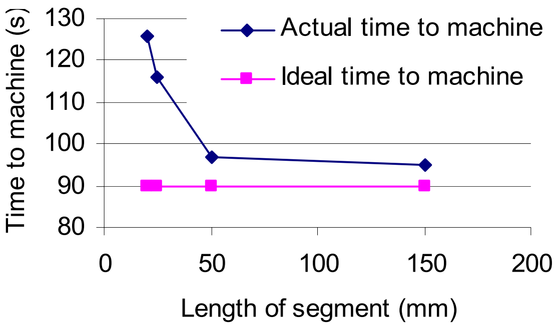
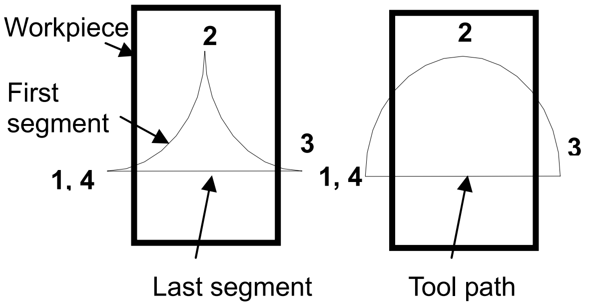


Figure 2: Machining time for 15m at 10m/min.



(a) (b)

Figure 3: Continuity and tool paths.

4.2 Feed acceleration loss

The other loss arises from the dynamics of the machine tool itself. The feed rate profile for each segment generally consists of acceleration, constant feed and a deceleration phase. The time required for acceleration and deceleration are dependent on the maximum feed rate the drive must reach and controller parameters. For shorter segments or extremely high feed rates, the acceleration and deceleration segment could be anywhere between 5 to 10% of the segment travel duration.

The results shown in figure 2 from experiments conducted indicate that the estimated time is up to 40% more than calculated time due to the above mentioned losses. This set of data is for a feed rate of 10 m/min.

5 BUFFER LOSSES

The G code is interpreted by a controller which breaks down the command into movements of drive axis and feeds it to the servo system. The controller has a buffer that holds a set of statements to be executed. There is a delay in machine tool every time the controller flushes the buffer and loads the next set of statements. Memory capacity of the buffer and transfer abilities limit the number of statements that can be loaded at a given time. This delay could be up to one second depending on the controller.

A single subroutine containing more statements than the value limited by buffer capacity automatically includes the delay time increasing cycle time. The shorter segments are disadvantageous as they increase the number of lines of code and can lead to including the delay time in the tool path. The buffer is also flushed every time a subroutine is completed. Therefore, by increasing the number of lines of code in one subroutine and decreasing the number of loops to be executed to attain the same tool path, the buffer losses can be minimized. Care has to be taken while increasing the number of lines in a single subroutine to ensure that the delay is not included in the subroutine and the end of subroutine when a loop is executed. This is demonstrated later in the case study as well.

6 ORIENTATION AND FEED LOSS

The orientation of the tool path can reduce the time necessary to obtain a particular feed by utilizing the fact that drives need to achieve only a fraction of the specified feed rates. In other words, acceleration, when perceived as a vector quantity, increases in magnitude with orientation for a specified feed. It has to be noted that this condition does not actually increase the feed or change the process mechanics as all the relevant parameters like engagement of the tool path in a workpiece, cutting direction and feed per tooth which controls the process outcomes are unchanged. Figure 4 illustrates the savings in machining time by rotating a straight line tool path originally machined parallel to the X feed drive axis after transformation to an orientation of 53.13°. The orientation was chosen as the coordinates of transformed tool path will remain integral. The slope of line segments originally parallel to the X axis will now be 4/3. There is up to a 4% savings in machining time accumulated over a certain number of passes. The savings are more pronounced for shorter segments. Experimental observations showed a strong positive correlation between the amount of time savings and the feed rate. Given a feed profile the savings can easily be quantified. Matlab simulation results for an exponential acceleration profile also corroborated the savings found during experimentation. The savings would be higher for linear or bi-quadratic acceleration profiles.

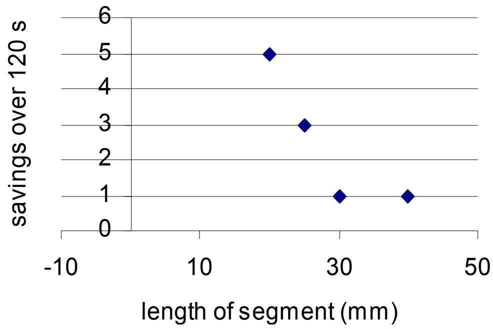
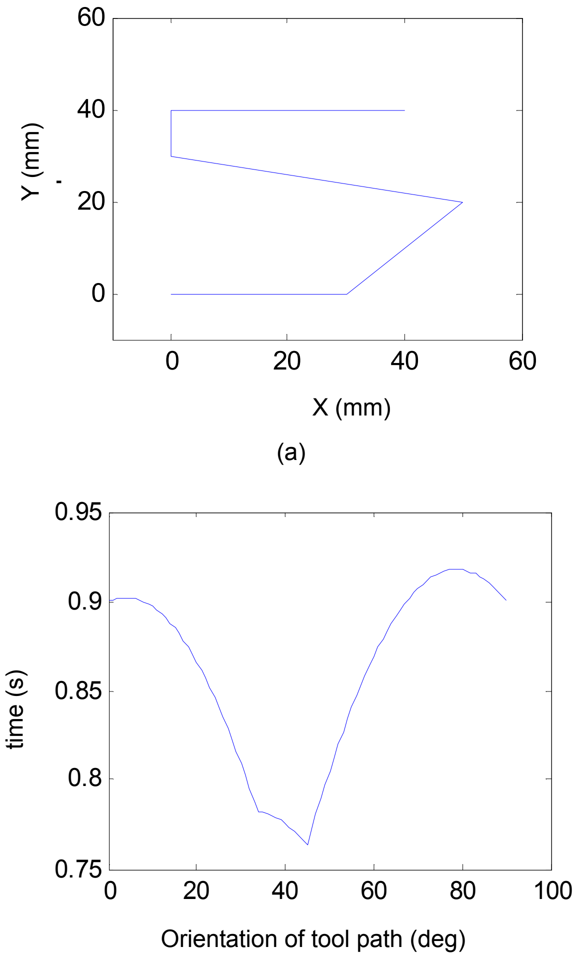


Figure 4: Time savings with 53.13° compared to 0°.

7 THEORETICALLY MINIMUM CYCLE TIME

The maximum feed rate is generally limited to f along all orientations by the machine tool manufacturer. However, the theoretical maximum feed rate that can be achieved, for any orientation, can be expressed as a vector sum of feeds generated by both drives with magnitude varying between f and f*√2. The value of feed rate is dependent on the actual orientation of the workpiece as one drive can be engaged at maximum feed while another at a lower rate to obtain the needed orientation. To obtain the theoretical minimum each segment is assumed to be machined at the highest possible feed rate. The minimum machining time with respect to theta shown in figure 5(b) is for the tool path in figure 5(a). Considering the special case of tool paths with just line segments, which is still the case in a lot of practical applications, the machining time is a continuous convex function and changes only when one of the segments becomes parallel to the drives. The problem is computationally efficient and has to be computed only for a fixed number of orientations. This does increase the feed per tooth if not compensated with a corresponding increase in cutting speeds.



(a)

(b)

Figure 5: Tool path and machining time for tool path.

8 DRIVE LOADS

The machine tool drives are coordinated to generate the motion and the total length of travel (L) and the pseudo measure for energy (E), which could be calculated by feed *x* length, are two important quantities that are observed. The first one is a measure of the wear on the drives and second one a measure of the electromagnetic load on the drives. The sum of the E measures for the X axis and Y axis is invariant with respect to any affine transformation. But the individual loads on the drives are dependent on the orientation of the workpiece. It is possible to balance the load on each drive for the parts being machined over a period of time to keep the usage (which affects, for example, wear) on the drives constant. The other significant effect of orientation is the length traversed and the maximum feed obtained by each drive. Figure 6 shows the variation in individual loads with orientation. The loads are generally dependent on the length of each segment and its orientation with respect to the axis. This follows a trend very similar to the machining time. Clearly, the orientation that reduces the individual feeds also tends to balance the loads on the drives. The major drawback of this scheme is that the total length traversed by the drives is maximum at the orientations where cycle time is the absolute minimum as the total length traveled by each drive has an inverse relationship with orientation. This is however accompanied by a reduction in the actual feed rates employed for each drive. The feed rate of individual drives X and Y can be 10-30% lower compared to the original orientation.

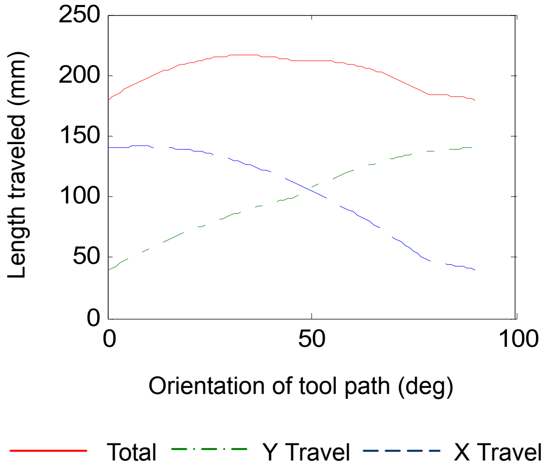


Figure 6: Drive travel for generating path in figure 4.

9 CASE STUDY

Tool path condition	Orientation 36.9° (seconds)	Orientation 0° (seconds)
Feed 1 (6m/min)	10	11
Feed 2 (10m/min)	13	14
Feed 1 – Improved buffer usage	5	
Feed 2 – Improved buffer usage	7	

Table 1: Excess time from ideal machining time.

The most common face milling tool paths employed are of a zig-zag style. A zig-zag tool path shown in figure 1 with 40mm segments and a 20mm step was run on the machine with orientations of 0° and 36.87°, at a constant feed rate. The results are shown in table 1. It can be seen that the influence of the orientation without increasing the base feed with respect to orientation is very small. But the savings do exist and as shown previously increase rapidly with increasing feed as would be the case in high speed machining. There is approximately 10% reduction in feed rate losses for the machine tool due to this transformation. Effectively utilizing the number of lines in the buffer of the controller at any time reduced the losses by an additional 50%.

10 CONCLUSION AND DISCUSSION

The primary aim of this paper is to demonstrate the advantages of orienting the part and tool path and efficient programming for face and rough end milling processes. An estimated 2-4% savings can be expected in cycle time through this approach without altering feed and more than 10-20% savings by utilizing the feed drive capabilities completely. The scheme is very effective for high feed rates and short segment based tool paths like specially designed tool path for edge quality optimization. Balancing the loads on the drives (L and E measures) will be better in the long run to insure uniform wear and tear on the machine tool over its life cycle.

The results presented in this paper are from a Matlab simulation written to generate the optimal orientation for any tool path composed of line segments. The future work involves developing a detailed theory for all curvilinear segments. The work will render itself more useful for practical applications when the system developed here is embedded in a controller to provide the optimal orientation and controller parameters when a part geometry and tool path is loaded. The feedrates and controller parameters should be set depending on the tool path. Optimization of the G-Code has to be done based on a set of recommended guidelines to achieve the maximum, balanced utilization of the machine tool for the workpiece batch. The concept can also be utilized for other processes involving table movements like stereolithography, FDM machines and chip shooters in electronic board assembly to obtain maximum benefit from the feed drive coordination.

11 ACKNOWLEDGEMENTS

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