COMPUTER NUMERICALLY CONTROLLED MILLING OF MONOBLOCK PROPELLER MODELS

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ABSTRACT

Computer numerically controlled (CNC) milling of monoblock propeller models presents several stimulating challenges for propeller manufacturers. This paper describes the technology for 5-axis CNC milling of monoblock propeller models developed and implemented at Dominis Engineering. The paper concentrates on a description of several key problems associated with 5-axis milling of monoblock propellers and describes procedures, techniques and special tools developed to allow 5-axis milling of monoblock propellers in one set-up.

1. INTRODUCTION

If our goal is computer numerically controlled (CNC) milling of monoblock propeller models to their final form, let us first examine our definition of CNC milling to final form. For the purpose of establishing a manufacturing objective, final form is defined in terms of maximum allowable scallop height over the entire surface of the machined propeller. For propeller models, maximum allowable scallop height is set at 0.0004 inch. Sculptured surfaces with residual scallops not greater than 0.0004 inch are considered to have been machined to final form since practically all hand finishing except for buffing of the surface to remove these miniature scallops has been eliminated.

In order to achieve this objective of machining to final form, the entire propeller model has to be machined under computer control, including propeller blade edges (by guiding the cutting tool around both the leading and trailing edge), propeller blade tip, fillets (either constant or variable radius, depending on the design) and portions of propeller model hub which cannot be turned on the lathe.

Maximum accuracy of the result will be achieved if the propeller model is machined in one set-up thus eliminating possible errors associated with fixturing and mis-alignment when repositioning the propeller model.

To accomplish these objectives and achieve efficient and cost effective CNC milling of monoblock propeller models to their final form, solutions to problems in several different areas of manufacturing had to be found. These areas are:

- Surface representation and propeller geometry
- Dynamics of the milling machine
- Cutter geometry
- Fixturing and propeller model set-up
- Interference checking and collision avoidance

2. SURFACE REPRESENTATION AND PROPELLER GEOMETRY

One way to describe the propeller geometry [1] is to specify three groups of data:

A. First group defines the basic profile of the propeller blade. Data in this group are typically non-dimensionalized with respect to chord length.
    1. Propeller blade profile offsets
    2. Profile camber line
    3. Camber line slope.

B. Second group defines the changes in the basic propeller blade profile at specified radii.
    1. Maximum camber
    2. Maximum thickness
    3. Maximum chord length

C. Third group defines position of propeller blade profiles at specified radii.
    1. Pitch
    2. Rake
    3. Skew

Another way to specify propeller geometry is to specify only propeller blade surface offsets at specified radii.

The first way is usually followed by propeller designers, while the second way is indicated in reverse engineering.

However, in both cases the density of data describing a propeller must be sufficient to allow proper operation of the chosen interpolation method which must be capable of computing offsets and normals at any point of the propeller surface.

Many interpolation methods are available for sculptured surfaces. We chose two-dimensional splines. Since this paper deals primarily with the manufacturing of monoblock propeller models we shall proceed under the assumption that the chosen interpolation method can specify offsets and normals anywhere on the propeller surface.

To get an idea of how many propeller blade sections have to be interpolated to achieve milling to final form, let us consider the following example:

Desired scallop height: 0.0004"
Radial span of propeller blade: 4."
Diameter of toroidal cutter: 1.75"
Radius of milling insert tip: 0.031"
Number of cuts per inch: 100
Number of interpolated section to be cut: 400

In addition to the propeller blade data, the fillet and the hub have to be specified.

Hub is a body of revolution, specified by its generating curve profile. The propeller blades pierce the hub at specified locations.

Propeller blade fillet can be described by a ball rolling around the propeller blade root touching at the same time the propeller blade and the hub. This fillet "rolling ball" can have a variable radius. There might be other ways to generate a fillet and compute its intersection with the propeller blade and with the hub, but this "rolling ball" method is the simplest.

3. DYNAMICS OF THE MILLING MACHINE

Because of the digital nature of numerically controlled milling machines, the cutter center path has to be broken into a series of linear segments. The shorter the segment, the better is the approximation to the true line. However, it is not efficient to settle beforehand for a constant, very short center path increment. It is more efficient to adopt variable segment lengths based on a constant deviation from the true line. Local line curvature, cutter radius and the allowed maximum deviation from the true line determine the appropriate segment length. Obviously, the segment length diminishes as the local line curvature increases, and vice versa. This approach also delivers warnings if the concave curvature radius gets smaller than the cutter radius, which would cause surface gouging. It is customary to set the maximum allowed deviation from the true line to 0.0001 inches. Set at 0.0001 inches the deviation from the true line surpasses the accuracy of the cutter radius and the accuracy of most milling machines.

The efficiency of variable length segment approach is not only in the program length but also in the program execution time. Since a long line segment implies a straighter path, long segment can be milled at higher speed than a short segment. Further more, to achieve the maximum benefit we should consider milling without stopping at the end of each segment. If the cutter has to slow down and stop at the end of each segment, and then accelerate at the beginning of a new segment, the cutter movement will become a series of jerky moves. Jerky, start-stop moves of the cutter will considerably compromise the quality of the machined surface. However, by cancelling acceleration/deceleration feature of the controller we introduce overshoot errors which increase with cutting speed and changes in direction of individual line segments. In order to eliminate possible overshoot errors while milling without stopping at the end of each line segment, we have to know dynamic parameters of the milling machine and its controller. Once measured, these dynamic parameters are used to compute the optimum speed for each segment. Selection of optimum speed for each line segment ensures smooth movement along each line segment, it minimizes cutting time and guaranties adherence to imposed tolerances.

When the milling machine is given a command to start moving from rest it reaches the commanded speed after a while and then it continues at constant speed. From that moment on, the actual position of the machine lags behind its theoretical position by an amount called following error. Assuming that the machine's initial acceleration is decaying exponentially, the following error is defined as $V \times T$ where V is machine speed and T is machine's time constant (see Figure 1). Machine's time constant is defined as the time required for the machine to reach 63.2% of V.

To measure time constant T of a milling machine, one must execute a movement in Y direction followed by a movement in X direction at speed V. When executing these movements acceleration/deceleration feature of the controller has to be disabled by using code G51.

It is difficult to determine where the actual path starts veering off. However, the 45° diagonal at the commanded corner cuts the actual path at the distance $0.520 \times V \times T$. This distance is called corner error.

For our milling machine time constant T is 0.033 seconds. Therefore for a feed rate V of 16 inches/min, the following error is 0.009 inches and the corner error is 0.004 inches.

Consider now the cutter center path of a cutter with a radius r, cutting a line having radius of curvature ρ. The radius of curvature can be either positive or negative. We have to break up the ideal cutter center path into segments of length s such that the cut line does not differ from the ideal line by more than a prescribed tolerance ϵ.

Length of cutter path segment can be computed by the following formula:

$$s=2\,|\rho-r|\sqrt{E(2-E)}$$

where $$E=\frac{\epsilon}{|\rho-r|}$$

This formula is valid for both $\rho < 0$ and $\rho > 0$.

This is a geometrical restriction on segment length if we do not want to stray too much from the prescribed line to be cut.

In order to determine the dynamical restriction on the feed rate V so that the overshoot or undershoot at segment corners do not introduce intolerable errors we can consider that the cutter center path is locally a circle. Therefore, to stay on that circle, approximated by a polygon with sides of length s, the following error should not exceed $s/2$:

$$V \times T = s/2 \quad \text{or} \quad V = s/2 \times T$$

For time constant $T=0.033$ seconds we have *speed* V [inches/minute] = $900 \times s$ [inches].

Formulae for s and V give a quantitative meaning to the intuitive reasoning: tighter the curve to be milled, more line segments will be required to represent that curve and slower will be the cutter speed to accurately mill that curve.

4. CUTTER GEOMETRY

A three dimensional curved surface is produced by multiple passes of a cutter. At each pass the cutter produces a groove. The bottom of each groove should lie on the surface and the sides of each groove should be above the surface. The deviation from the true surface of a milled piece can therefore be described by two parameters: deviation of the groove bottom and height of the scallop (cusp).

This deviation concept is best visualized with a spherical (ballnose) cutter. In order to cut a proper groove we have to guide the center of the ball along the groove at the distance from the surface equal to the radius of the ball, in the direction along the normal to the surface.

To simplify matters let us first consider ballnose cutters, introducing dovetail and toroidal cutters later. Let us also consider cutting passes to be plane curves, without impairing the validity of the discussion.

All what was discussed so far refers to a single pass over the surface. The whole surface is traversed in a series of closely adjacent passes. The scallop heights between passes depend on the ball radius. The larger the radius the lower the scallop. Typically, for 1 inch ball diameter and step size of 0.050 inches the scallop heights are close to 0.0005 inches. The ball nose cutter shaft direction is, up to a point, independent of the normal to the surface at the cutting point. The only requirement is that the cutter center is on the normal to the surface. The cutter radius is always the same and so is the distance from the ball center to the cutting point.

The dovetail cutter with sharp inserts is restricted in its attitude: the cutter shaft must be perpendicular to the plane curve. That means that only the normals to the plane curve have to be known, which are easier to compute than the normals to the surface. The scallop height between adjacent passes depends on the angle of the dovetail cone. The scallops have a sharp triangular profile. The cutter radius is constant, which simplifies checking for gouging of concave surfaces.

The toroidal cutter combines good and bad features of both spherical and dovetail cutters. The cutter shaft direction is flexible, albeit limited. Cutter inserts are round and small in comparison with cutter diameter. This feature is favourable to scallop heights, scallop profile and step size. However, normals and tangents to the surface must be known since the "virtual spherical cutter" radius varies with the angle between the cutter shaft, normal to the surface and the tangent at the curve to be cut at the cutter contact point.

Larger the cutter diameter more vulnerable will the surface be to undercutting or overcutting due to inaccuracies in surface normals.

As the inserts wear during machining, it would be necessary to perform cutter diameter compensation to ensure accuracy of the machined surface. However, cutter compensation cannot be accomplished for sculptured surfaces without the information about the contact point, normal to the surface at the contact point, insert wear information and measurement of the milled surface on the fly.

Three dimensional cutter compensation for machining of sculptured surfaces cannot be performed by commercial controllers since the controller receives only the coordinates of the tool center.

To resolve problems with tool wear and three-dimensional cutter compensation, tool wear is monitored and the cutter is replaced at the end of its life with a new one. The replaced tool might have a slightly different diameter and therefore has a different cutter center path file from its predecessor.

We found that on the average the applicable insert grade lasts for hardened stainless steel 7 hours at 225 surface feet/minute and feed rate of 6.4 inches/min, for titanium 6 hours at 160 surface feet/minute and feed rate of 5.2 inches/min, and for inconel 40 minutes at 70 surface feet/minute and feed rate of 2.5 inches/min.

Another set of numbers can be used for planning purposes: if a propeller blade part takes one hour to mill in aluminum or brass, it would take five hours in hardened stainless steel, seven hours in titanium and 10 hours in inconel.

Of course, for any specific application, more accurate figures for expected tool life and machining time have to be obtained by experiment.

5. FIXTURING AND PROPELLER MODEL SET-UP

For propeller models up to 24 inches in diameter we chose to mount the propeller model into a vertical rotary table (A-axis, 5th axis). Vertical rotary table is mounted on a horizontal rotary pallet (B-axis, 4th axis). The propeller model is oriented so that the propeller blade axis is parallel to the Z-axis (3rd axis) while the propeller shaft axis is parallel to the X-axis (1st axis). When propeller model is mounted in this fashion both face and back of the propeller blade, fillet region and hub region are accessible at the same time. Necessity for flipping of the propeller model, with all its associated problems, has thus been eliminated. The center of the propeller model must coincide with the intersection of A and B axis. Toroidal cutters are used for machining almost the entire propeller model blade. For machining of blade-fillet, fillet and fillet-hub regions several different diameter ball nose cutters are required.

For propellers larger than 24 inches in diameter, set-up on the A-axis becomes impractical. This is due to the tool lengths and the diameter of the A-axis rotary table. These larger propeller models have to be milled one side at a time. When milling in this set-up propeller blades have to be supported by a special fixture. After one side is milled and markers on it are established and measured, the propeller is flipped and markers indicated and brought to the position where they should be. However, instead of physically moving the propeller into desired position, it is easier to compute a transformation matrix between the measured position and desired position and subject the cutter center path to three angular and three linear increments. Once the cutter center path is adjusted milling of the other side of propeller can proceed.

6. INTERFERENCE CHECKING AND COLLISION AVOIDANCE

When machining propeller models in one set-up on a 5-axis milling machine it is necessary to perform extensive checking for possible interference between the tool and propeller model, between the tool and fixtures, and between propeller model and spindle head. When interference is detected, to avoid collision the computer aided manufacturing (CAM) system selects through an iterative process an alternate orientation of the tool with respect to the propeller model. Of course, there are other restrictions to be observed, such as capabilities of insert cutting edges and ranges of movements of machine's linear and rotary axis.

In order to shorten the computation time when checking for interference, our CAM system searches a less dense set of propeller sections above the section to be cut. For every surface contact point the CAM system finds the potential interference points with the appropriately defined cutter shaft when in standard orientation. Based on the largest interference, it calculates the new tool position to avoid collision. The new tool position is defined by the angle by which the tool shank has to be inclined while in the plane defined by the standard shank orientation and the normal to the propeller blade surface at the contact point. The sequence of these angles has to be inspected in order the eliminate abrupt avoidance actions which could lead to rather fast motions of either rotary axes.

7. REFERENCES

[1] J. Lester Klein, "A Rational Approach to Propeller Geometry"; Propellers '75, SNAME Symposium, Philadelphia, July 1975.

[2] Draško Gospodnetić, "Computer Numerically Controlled Milling of Ship Model Propellers"; Canadian Maritime Industries Association (CMIA) 42nd Annual Technical Conference, Montreal, February 1990.

[3] Draško Gospodnetić and Slobodan Gospodnetić, "Computer Numerically Controlled Milling of Model Propellers in Hard Metals"; CMIA 44th Annual Technical Conference, Ottawa, February 1992.

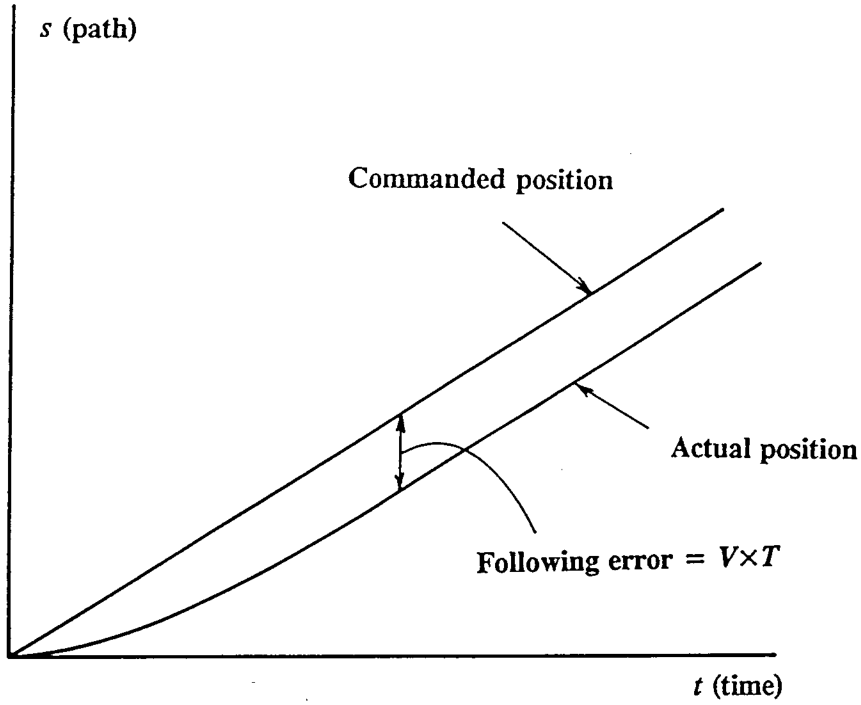

FIGURE 1 - FOLLOWING ERROR

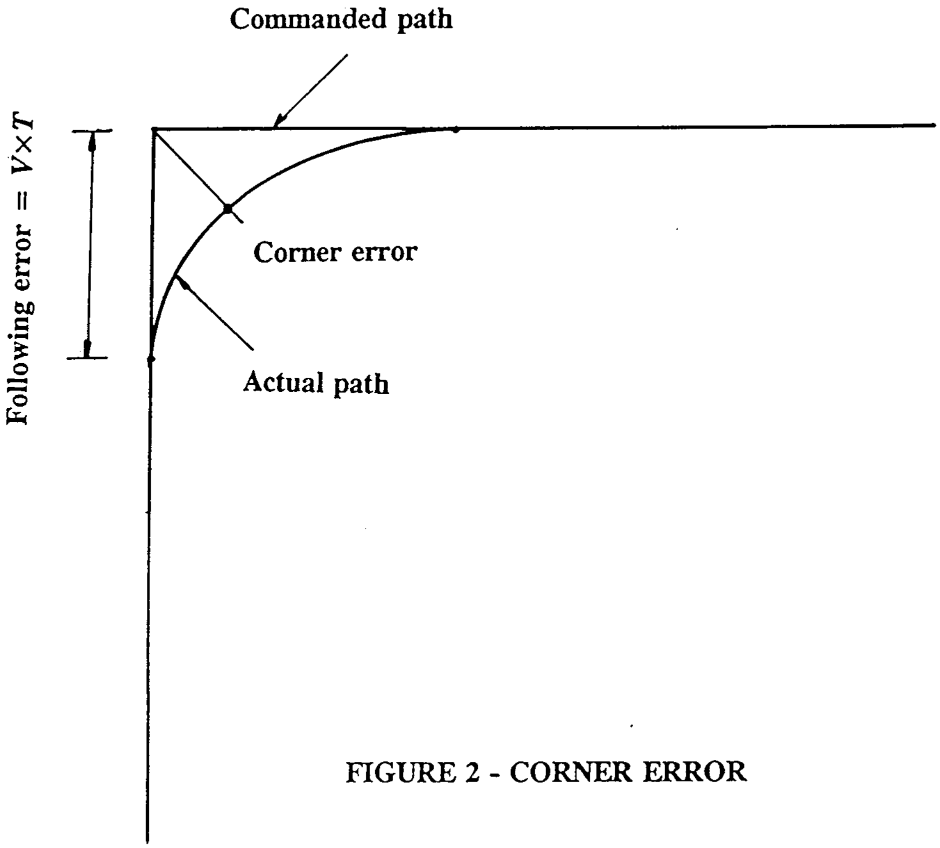

FIGURE 2 - CORNER ERROR