Non-linear kinematics of a 5-axis milling machine

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Five-axis milling machines, used for many years in the aerospace industry, also prove their advantages in the accurate and fast machining of smaller sized and complex workpieces such as propellers, impellers, moulds, EDM electrodes and others. At the moment, the generation of an NC-program for multi-axis milling machines proceeds in several stages such as workpiece geometry, cutter location, NC-postprocessor.

This paper describes a step-wise development of a NC-postprocessor for a-axis milling machine. One issue is related to post-processor development namely : a part coordinate to machine coordinate transformation. The post-processor was implemented for the MAHO600E milling machine using Pascal programming. The functionality was developed based on the algorithms formulated for the solution of the issues presented. A converter of the cutter location file based on inverse kinematics has been developed and tested.

1. Introduction

Innovations in the field of mechanical engineering have enhanced the involvement of milling robots in various manufacturing processes. Nowadays, milling machines, guided by a computer system, are employed to produce free-shape surfaces to supply the need of mass manufacturing plants, such as: the automobile, airplane and ship-building industry. Milling machines are becoming more and more popular due to their ability to handle geometrically complex workpieces composed of raw material (rubber, wood, stone, metal, plastic, etc). Moreover, up-to-date milling robots are characterized by a high material removal rate and by an efficient surface finish up.

Unfortunately, it is not all rosy. Several physical phenomena, such as: machine kinematics, thermal effects, static and dynamic loading, common-cause failures, clamping and spindling of the cutting device, often affect the quality of the desired surface. However, the particular impact of the machine kinematic-geometric errors,(which seems to be the most significant "bug-bear" [1]), constitutes the main subject of our paper.

Let us first introduce a typical configuration of the prototype 5-axis milling robot with the rotary axes on the table depicted in Fig.1.1 The cutting tool (which has 5 degrees of freedom) is guided by axial commands carrying the 3 spatial (Cartesian) coordinates of the tool-tip in the machine coordinate system *M* and the two rotation angles (Fig.1). The supporting CAM software generates a successive set of coordinates (usually called cutter location points or CL-points) in the workpiece coordinate system *P*. Typically, the CAM software distributes the CL-points along a set of curves which constitutes the so-called zigzag or spiral tool-path (Fig.2). An appropriate transformation into the *M*-system generates the set of the machine axial commands providing reference inputs for the servo-controllers of the milling robot.

In order to guide the tool between the prescribed CL-points, an axial command translates the centers of rotation (Fig.1) and simultaneously rotates the *P*-coordinates. Consequently, the tool-tip (affected by the machine kinematics) "travels" in the *P*-system along a non-linear trajectory (Fig.3). In order to ensure a prescribed tolerance, the standard CAM software "estimates" the local errors and incorporates additional cuts (if applicable) into a single output-block. However, such a strategy invokes a substantial increase of the CL-points and consequently a substantial increase of the machining time. For instance, it has been documented that the total time of producing a die or mold between the design and the inspection, varies from 1200 to 3800 h. with a finishing up time of about 30-50%.

Therefore, recent papers have displayed a number of sophisticated methods to optimize a zigzag pattern[1-3] often combined with techniques dealing with the geometric complexity of the workpiece[4,5]. Moreover, a variety of off-line methods are available to generate a suitable non-uniform tool-path, for instance: the neural network modeling approach[5] and the Voronoi diagram technique[6]. However, a robust algorithm to generate such complicated patterns is still an open problem. On the other hand, the "structured" zigzag/spiral approach is simple and robust and therefore suitable to be embedded into conventional CAM-applications.

Our survey clearly indicates the need for further research in the tool-path planning of milling robots. In the meantime, we propose to develop the non-linear kinematics of 5-axis milling machine.

we first define the required surface and the surface generated by non-linear trajectories. Next, we present the real machining that our contribution provides a non-linear kinematics of a 5-axis milling machine.

2. The non-Linear kinematics

In order to calculate the tool-path between successive positions p and $p+1$, we first transform the part-surface coordinates into the machine coordinates. Secondly, the rotation angles, denoted by a and b, and the corresponding machine coordinates $M \equiv M(t) \equiv (X(t), Y(t), Z(t))$ are assumed to change linearly between the prescribed points.

Namely,

$$\begin{aligned} M(t) &= tM_{p+1} + (1-t)M_p, \\ a(t) &= ta_{p+1} + (1-t)a_p, \\ b(t) &= tb_{p+1}t + (1-t)b_p, \end{aligned}$$

where t is a fictitious time coordinate ($0 \leq t \leq 1$) and M_p the machine coordinate at the point p. The corresponding rotation angles are given by

$$a_p=\arctan(i_p/j_p),\ b_p=\arctan((i_p^2+j_p^2)^{1/2}/k_p),$$

where (i, j, k) denotes the vector normal to the required surface. We invoke an inverse kinematics equation technique e.g. [3],[8]. Observe that the inverse kinematics are depending upon the structure of a machine. For our machine configuration (TTTRR, see Fig.1) the resulting inverse kinematics equations, involving two rotations and three translations, are given by

$$P= (A^{-1}(B^{-1}(M-C) -T)) -R,$$

where, $P \equiv P(t) \equiv (x(t), y(t), z(t))$, R, T and C are respectively the workpiece coordinates, the coordinates of the origin of the worpiece in the rotary table coordinates, coordinates of the origin of the rotary table coordinates in the tilt table coordinates and the origin of the tilt table coordinates in the cutter center coordinates. $A \equiv A(a(t))$, $B \equiv B(b(t))$, are respectively denoting the matrices of rotation around the primary(the rotary table) and the secondary(tilt table) axes.

Finally, we derive above transformation for the configuration presented in Fig.1. The transformation from the worpiece coordinates to the machine coordinates is given by

$$\begin{aligned} X_m =&(X_w + R_x)\cos(a)\cos(b) - (Y_w + R_y)\cos(b)\sin(a) \\ &+T_x\cos(b) - (Z_w + R_z + T_z)\sin(b) + OT_x \end{aligned}$$

$$Y_m = (X_w + R_x)\sin(a) + (Y_w + R_y)\cos(a) + T_y + OT_y\ ,$$

$$\begin{aligned} Z_m =& (X_w + R_x)\sin(b)\cos(a) - (Y_w + R_y)\sin(a)\sin(b) \\ &+ T_x\sin(a) + (Z_w + R_z + T_z)\cos(a) + OT_z \end{aligned}$$

with the inverse transformation

$$\begin{aligned} x =& (x - C_x)\cos(a)\cos(b) + (z - C_z)\cos(a)\sin(b) \\ &- T_x\cos(b) - (y - C_y - T_y)\sin(b) - R_x \end{aligned} ,$$

$$\begin{aligned} y =& -\sin(a)\cos(b)(C_x + x) - (z - C_z)\sin(a)\sin(b) \\ &+ T_x\sin(a) - (y + C_y + T_y)\cos(b) - R_y \end{aligned} ,$$

$$z = -\sin(b)(x + C_x) + \cos(a)(z - C_z) - T_z - R_z .$$

Fig.3 shows the tool-paths between the two successive positions (0,0,0) and (0.1,0.1,0.1) for $a(0)=70^0$, $a(1)=75^0$, $b(0)=70^0$, $b(1)=80^0$ and for $a(0)=70^0$, $a(1)=80^0$, $b(0)=70^0$, $b(1)=85^0$

Remarks

In considering the conventional kinematics of a five axis milling machine, each orientation of the tool-axis *(i, j, k)* can be achieved at two different positions of the rotary axes. However, a limited range of the rotary axes often eliminates one of these steps. If the principal B-axis is zero *(i=0, j=0, k=1)*, then any value for the second axis is admissible. This is called a degenerate position in that the C-axis is parallel to the tool axis and therefore has no influence on the orientation of the tool axis with respect to the clamping plane.

If the tool axis is moved from *B>0* to *B<0*, then the tool axis goes through the degenerate position *(B=0 and i=0, j=0, k=1)*.

Consider two successive tool positions on the surface *P(u,v)* and introduce the coordinate transformation from the workpiece to the machine coordinate system, where $P=(X_w, Y_w, Z_w)$ is the coordinates system for the part surface and *T3(Rx, Ry, Rz)* is workpiece offsets. The distance information then becomes:

$P(X_w, Y_w, Z_m)$ is the workpiece coordinate of the cutting tool,

T3(Rx = 0, Ry = 0, Rz = 165) is the workpiece position on the rotary table *A* and 165 mm is the distance from the origin of the *A*-axis to the origin of the workpiece in direction of the Z-axis.

T2(Tx = 0, Ty = 0, Tz = -250.314) is the distance between the rotary table and the tilt table.

T1(OTx = 298.92, OTy = 177.278, OTz = -(430 - 138.594, tool length cutter) is the distance between the end cutter center and the tilt table origin.

3. Experiment results

Next, we illustrate a performance of the proposed procedure. The following example illustrates a non-linear kinematics of 5-axis milling machine procedure. Fig.4 display a typical required surface, and a maximum allowed distance between the CL-points ($h_{\max}$=0.003).

A conventional tool path (20x20) is shown in Fig.4, A typical testing surface sequence is given by a Bi-cubic Bezier surface where $B(u,v)$ denotes a Bezier surface having the control points:

$$B_x = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 12 & 12 & 12 & 12 \\ 24 & 24 & 24 & 24 \\ 36 & 36 & 36 & 36 \end{bmatrix}, B_y = B_x^T,$$

$$B_z = \begin{bmatrix} -16 & -8 & -6 & 0 \\ -8 & -6 & 0 & -2 \\ -6 & 0 & -2 & 0 \\ 0 & -2 & 0 & 0 \end{bmatrix}.$$

Surface P_{10} produced by the milling machine MAHO-600E is shown in Fig. 5. The tool radius r=3 mm. The accuracy of milling has been analysed by means of the Surface roughness machine.

Conclusions and recommendations

During the development of the non-linear kinematics algorithm, a number of issues have been solved.

1. The general method of transforming the part coordinates to machine coordinates was demonstrated using the method of rotation vectors. The transformation was solved for one reference configurations. The transformation equations had to be corrected for actual machining requirements. The correction involved the machine coordinate A (rotation of the *a-axis*). The first correction limited the values of the machine coordinate A to only its positive values. The second correction incremented the computed values to take into accumulated rotation about the A-axis. The implemented solutions work for the sample part manufactured but should be investigated for more sample parts to ascertain the generality of the solutions implemented.
2. The non-linear kinematics developed has limited functionality. It supports the multi-axis mode processing for the MAHO 600E machine. It supports the following post-processor words such as tool number, feed rate, spindle speed, dwell. A limited number of NC words are supported. The non-linear kinematics developed :
   - Performs part coordinated to machine coordinate transformation for one reference systems.
   - Calculates the machine zero point for assumed machine configurations.
   - Checks if the generate NC code exceeds the defined machine limits.
   - Generates NC code for for 5-axis machining

Recommendations for further study

The work on the non-linear kinematics for the MAHO 600E opens a lot of research opprtunities relating to the design of the post-processor and the use of the MAHO 600E machine.

1. Link with the CAD/CAM software.
2. Post-processor CAM functionality : A view to add CAM functionality to the post-processor should be investigated.
3. Link with tool verification software.
4. Enhancements to the non-linear kinematics such as, machining time, linearization, and tool inclination.

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