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Key techniques of symmetrical machining

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Abstract To improve the machining efficiency of large symmetrical freeform surface, this paper proposes a new machining method: symmetrical machining (SM). Based on the concept of collision avoidance plane (CAP), collisions among cutters or headstocks are avoided, and the area of machining residue is controlled effectively. Machining residue is eliminated due to proper design of symmetrical tool in mechanism and control project. Taking 5-axis symmetrical machine with columnar headstocks and flat cutters as example, this paper proposes collision avoidance algorithm. Finally, using a twin-skeg ship model surface as an example, the method is applied to avoiding collisions in original tool path. Simulation and real machining results show that the scheme is practical. Furthermore, the machining efficiency of SM is improved 85% more than that of the traditional single cutter technology.

Keywords symmetrical machining (SM), collision, machining residue, collision avoidance plane (CAP).

1 Introduction

Due to the ever-increasing competition in the marketplace and the rapid development of numerical control (NC) machining technology, the freeform surface machining with high efficiency has become a research focus. Methods for improving machining efficiency for the freeform surface fall into five types: (1) multi-axis machining technology[1−2], (2) high-speed cutting technology[3−4], (3) machining process planning optimization[5−6], (4) optimization of tool path[7−8], and (5) cutter structure innovation[9−10]. All these methods are based on single cutter principle. For large symmetrical freeform surface, however, these methods do not make full use of symmetrical characteristic, leading to insufficient improvement of the machining efficiency.

To greatly improve the machining efficiency of large symmetrical freeform surface, we propose a new machining method: symmetrical machining (SM). In order to avoid collision and control machining residue effectively, a new concept of collision avoidance plane (CAP) is presented, and the design theory of the SM machine tool is studied. Based on 5-axis NC machine with columnar headstocks and flat cutters, we propose a collision avoidance algorithm. Finally, taking a twin-skeg ship model surface as an example, the algorithm is testified.

2 Symmetrical machining

As its name implies, symmetrical machining is a kind of machining method in allusion to large symmetrical freeform surface (see Fig.1). At any instant in the symmetrical machining process, there are two identical cutters working in the same state. Their position, orientation, spindle rotating speed, *etc*., are all symmetrical with respect to the plane of symmetry.

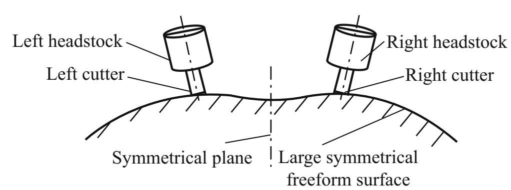

Fig.1 Symmetrical machining

Symmetrical machining can greatly improve machining efficiency of large symmetrical freeform surface. However, the cutters or headstocks may collide near the symmetrical plane (see Fig.2). In order to avoid collision, a region near the symmetrical plane must be reserved without machining, resulting in a machining

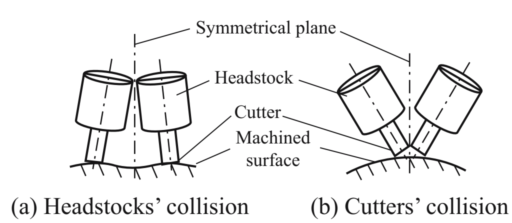

Fig.2 Collision in SM

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residue. For high efficiency, the area of machining residue must be strictly controlled. So, the key techniques are as follows: avoiding collision among headstocks or cutters, ensuring the least machining residue, and eliminating the machining residue.

As shown in Fig.3, collision avoidance planes are two planes which are parallel and symmetrical with respect to the symmetrical plane of the machined surface. The distance δ between the two planes is a safety margin for avoiding collision, generally 1∼10 mm. Collisions can be avoided by preventing the cutters and headstocks from getting across CAPs, and the machining residue can be effectively controlled by setting the distance δ within a suitable value.

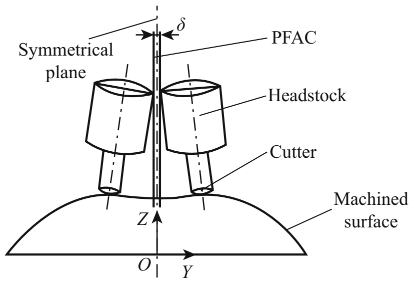
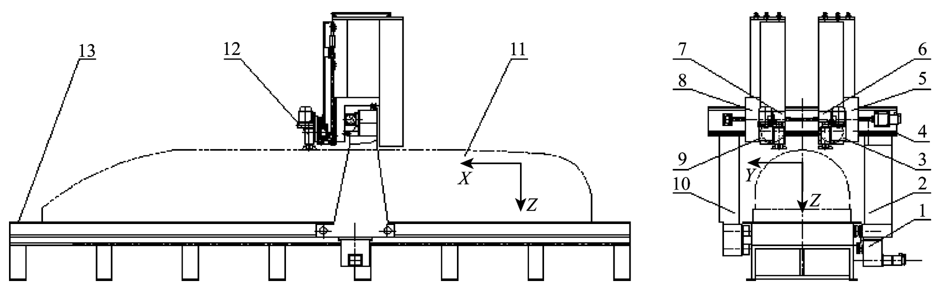


Fig.3 Plane for avoiding collision in SM

3 Symmetrical machining tool

3.1 Mechanism of 4-axis symmetrical machining tool

The main parts of the symmetrical machining tool are shown in Fig.4. The left and right columns connect the beam to form a gantry-type mechanism, which can move along X-axis on the worktable. Installed on the beam, left and right transverse sliding saddles can move in opposite directions along Y-axis. The left and right vertical sliding saddles are installed respectively on the left and right transverse horizontal sliding saddles, and they can move along Z_1-axis and Z_2-axis respectively. Similarly, the left and right slewing heads are installed respectively on the left and right vertical sliding saddles. They can rotate around A_1-axis and A_2-axis respectively. On each of the slewing heads a cutter is installed.



1–Gantry-type horizontal moving mechanism (X-axis); 2–Right column; 3–Right slewing table (A_2-axis); 4–Beam; 5–Right transverse horizontal sliding table (Y_2-axis); 6–Right vertical sliding table (Z_2-axis); 7–Left vertical sliding table (Z_1-axis); 8–Left transverse horizontal sliding tables (Y_1-axis); 9–Left slewing table (A_1-axis); 10–Left column; 11–Machined surface; 12–Cutter; 13–Worktable

Fig.4 Four-axis symmetrical machining tool

3.2 Computerized numerical control (CNC) system of the 4-axis symmetrical machining tool

The CNC system structure of the 4-axis symmetrical machining tool is designed according to the mode of "industrial computer + motion controller + servo drive system", as shown in Fig.5.

3.3 Realization of 4-axis symmetrical machining

According to the definition of symmetrical machining, the two cutters of the 4-axis symmetrical machining tool should not only move synchronously in the same direction along X-axis and Z-axis, but also move synchronously in opposite direction along Y-axis and A-axis.

Because the two cutters share one X-axis servo drive system, they can move synchronously in the same direction along X-axis. The two cutters share one Y-axis servo drive system and are driven by special ball-screws with opposite direction screws on each side, so they can move synchronously in opposite direction along Y-axis. Such design scheme in Y-axis can meet the requirements of symmetrical machining, and save one set of servo drive system.

Because the two cutters are driven along Z-axis and A-axis respectively by their own drive systems, the requirements of symmetrical machining along Z-axis and A-axis can only be met through circuit design.

Z_1-axis and Z_2-axis servo drivers connect the same terminal CN7 *via* KA1 and KA2 relays respectively (see

Fig.6). If KA1 and KA2 relays switch on simultaneously, the Z_1-axis and Z_2-axis servo drivers will receive identical drive signals, ensuring the cutter synchronization along Z-axis. If one of the relays switches on and the other switches off, only one of the cutters will move. So one cutter can be raised to quit cutting, and the other is used to finish the cutting operations. This ensures that machining residue could be cleared up without collision.

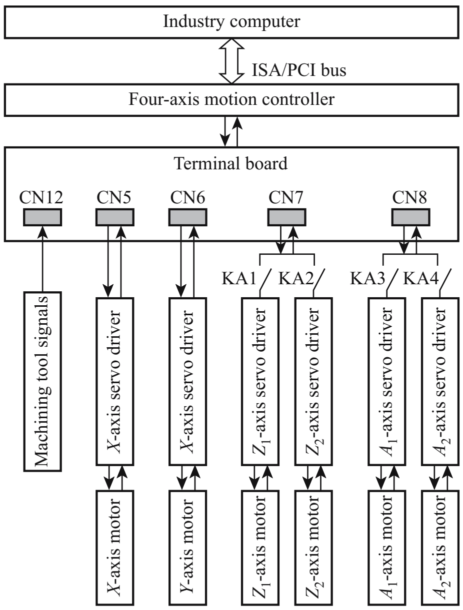


Fig.5 CNC system of a 4-axis symmetrical machining tool

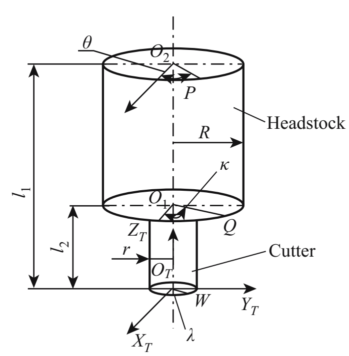


Fig.6 Headstock, cutter and coordinate system

Similarly, A_1-axis and A_2-axis servo drivers connect the same terminal CN8 *via* KA3 and KA4 relays respectively. If KA3 and KA4 relays switch on simultaneously, the A_1-axis and A_2-axis servo drivers receive identical drive signals, ensuring the cutter synchronization along A-axis. When the motor phase-sequence of A_1-axis is opposite to the one of A_2-axis, the two cutters can rotate in opposite directions around A-axis.

4 Modeling of headstock and cutter

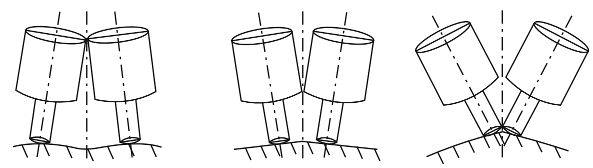
Taking 5-axis SM tool with columnar headstock and flat cutter as an example, the modeling of headstock and flat cutter is set up (see Fig.6). R and r are the radii of the headstock and cutter respectively, generally $R > r$. l_1 and l_2 are the distance from the end of the flat cutter to the up end of the headstock and down end of the headstock respectively. $\{O_T; X_T, Y_T, Z_T\}$ is the cutter coordinate system. P, Q, and W are any three points in the end circles of up headstock, down headstock and flat cutter respectively. θ, κ, and λ are three angles of X_T axis and the projections of the rotary radii O_2P, O_1Q, O_TW in the plane $X_TO_TY_T$ respectively. $\boldsymbol{r}_{TP}$, $\boldsymbol{r}_{TQ}$, and $\boldsymbol{r}_{TW}$ are the position vectors of points P, Q and W respectively, then

$$\boldsymbol{r}_{TP} = [x_{TP} \quad y_{TP} \quad z_{TP}]^{\mathrm{T}} = [R\cos\theta \quad R\sin\theta \quad l_1]^{\mathrm{T}},$$
$$\boldsymbol{r}_{TQ} = [x_{TQ} \quad y_{TQ} \quad z_{TQ}]^{\mathrm{T}} = [R\cos\kappa \quad R\sin\kappa \quad l_2]^{\mathrm{T}},$$
$$\boldsymbol{r}_{TW} = [x_{TW} \quad y_{TW} \quad z_{TW}]^{\mathrm{T}} = [R\cos\lambda \quad R\sin\lambda \quad 0]^{\mathrm{T}},$$

where $-180° \leqslant \theta, \kappa, \lambda \leqslant 180°$

5 Collision avoidance algorithm

In the case of $R > r$, there are three kinds of collision in SM: up end collision of the headstocks (see Fig.7(a)), down end collision of the headstocks (see Fig.7(b)), and cutters collision (see Fig.7(c)).



(a) Up end collision of the headstocks (b) Down end collision of the headstocks (c) Cutters collision

Fig.7 Collision of headstocks and cutters

The relationship of machined surface, headstocks, cutters, CAPs and machine coordinate system is shown in Fig.8. The coordinate plane XOZ is the symmetrical plane of the machined surface. Due to the symmetric characteristics, we only need to consider one of the two symmetrical sides, such as right side in this paper. L is cutter location point, which is the cutter coordinate origin O_T. C is the cutter contact point. M, N, and K are the closest points to the CAP which are on the end circles of the up headstock, down headstock and flat cutter respectively. $\boldsymbol{r}_M$, $\boldsymbol{r}_N$, and $\boldsymbol{r}_K$ are the position vectors of points M, N and K. Let $\boldsymbol{r}_M = [x_M \quad y_M \quad z_M]^{\mathrm{T}}$, $\boldsymbol{r}_N = [x_N \quad y_N \quad z_N]^{\mathrm{T}}$, $\boldsymbol{r}_K = [x_K \quad y_K \quad z_K]^{\mathrm{T}}$. $\boldsymbol{i}$ is the tool-axis vector, and $\boldsymbol{i} = [i_x \quad i_y \quad i_z]^{\mathrm{T}}$. $\boldsymbol{i}_0$ represents the initial value of the tool-axis vector, let $\boldsymbol{i}_0 = (0 \;\; 0 \;\; 1)^{\mathrm{T}}$.

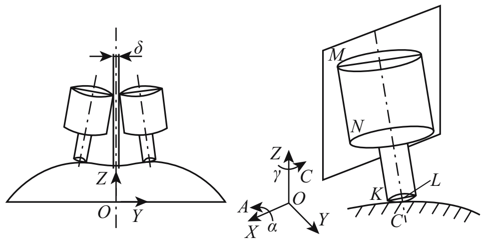


Fig.8 Machined surface, headstock, CAPs and machine coordinate system

First study the condition of avoiding the up end collision of the headstock. In general, $i_z \geqslant 0$, the up end collision precondition of headstocks is $i_y \leqslant 0$, and the collision avoidance condition is $y_M \geqslant \delta/2$. Now compute y_M. α represents the angle between the Z axis and tool-axis vector $\boldsymbol{i}$, and $0° \leqslant \alpha \leqslant 180°$. γ represents the angle of the Y axis and the projection of the tool-axis vector $\boldsymbol{i}$ in XOY plane, and $-180° \leqslant \alpha \leqslant 180°$. $\boldsymbol{M}_A[\alpha]$ and $\boldsymbol{M}_C[\gamma]$ are the rotary matrixes, and then we have

$$\boldsymbol{M}_A[\alpha] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix},$$

$$\boldsymbol{M}_C[\gamma] = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$\boldsymbol{M}_C[\gamma] \cdot \boldsymbol{M}_A[\alpha] \cdot \boldsymbol{i}_0 = \boldsymbol{i}. \tag{1}$$

By substituting $\boldsymbol{i}_0$, $\boldsymbol{i}$, $\boldsymbol{M}_A[\alpha]$ and $\boldsymbol{M}_C[\gamma]$ into (1) and simplifying it, we have

$$\begin{cases} \cos\alpha = i_z, \\ \tan\gamma = -i_x/i_y. \end{cases} \tag{2}$$

$\boldsymbol{r}_L$ represents the position vector of cutter location point L in machine coordinate system. Let $\boldsymbol{r}_L = [x_L \ \ y_L \ \ z_L]^{\mathrm{T}}$. $\boldsymbol{r}_P$ represents the position vector of point P in machine coordinate system, then

$$\boldsymbol{r}_P = [x_P \ \ y_P \ \ z_P]^{\mathrm{T}} = \boldsymbol{M}_C[\gamma] \cdot \boldsymbol{M}_A[\alpha] \cdot \boldsymbol{r}_{TP} + \boldsymbol{r}_L. \tag{3}$$

By substituting $\boldsymbol{r}_{TP}$, $\boldsymbol{r}_L$, $\boldsymbol{M}_A[\alpha]$ and $\boldsymbol{M}_C[\gamma]$ into (3) and simplifying it, we have

$$y_P = R\sin\gamma\cos\theta + R\cos\gamma\cos\alpha\sin\theta + l_1\cos\gamma\sin\alpha + y_L. \tag{4}$$

Let $\frac{\partial y_P}{\partial \theta} = 0$, then

$$\tan\theta = \frac{\cos\alpha}{\tan\gamma}. \tag{5}$$

By substituting (2) into (5) and simplifying it, we have

$$\theta_M = \begin{cases} 180° + \arctan[-i_z i_y/i_x], & i_x < 0, \\ \arctan[-i_z i_y/i_x], & i_x \geqslant 0, \end{cases} \tag{6}$$

$$y_M = R\sin\gamma\cos\theta_M + R\cos\gamma\cos\alpha\sin\theta_M + l_1\cos\gamma\sin\alpha + y_L. \tag{7}$$

Similarly, in general $i_z \geqslant 0$, the down end collision precondition of headstocks is $i_y > 0$, and the condition of avoiding collision is

$$y_N \geqslant \delta/2, \tag{8}$$

where

$$y_N = R\sin\gamma\cos\kappa_N + R\cos\gamma\cos\alpha\sin\kappa_N + l_2\cos\gamma\sin\alpha + y_L, \tag{9}$$

$$\kappa_N = \begin{cases} \arctan[-i_z i_y/i_x] - 180°, & i_x < 0, \\ \arctan[-i_z i_y/i_x], & i_x \geqslant 0. \end{cases} \tag{10}$$

Similarly, in the general case of $i_z \geqslant 0$, the cutter collision precondition of headstocks is $i_y > 0$, and the condition of avoiding collision is

$$y_K \geqslant \delta/2, \tag{11}$$

where

$$y_K = r\sin\gamma\cos\lambda_K + r\cos\gamma\cos\alpha\sin\lambda_K + y_L, \tag{12}$$

$$\lambda_K = \begin{cases} \arctan[-i_z i_y/i_x] - 180°, & i_x < 0, \\ \arctan[-i_z i_y/i_x], & i_x \geqslant 0. \end{cases} \tag{13}$$

6 Collision avoidance realization

Based on the above algorithm, the tool path without collision can be obtained by eliminating the collision in the original tool path. To save computation time, the possible collision region should be specified earlier. Only the tool path in the possible collision region needs to be verified. L ($\boldsymbol{r}_L = [x_L \ \ y_L \ \ z_L]^{\mathrm{T}}$) represents the any point on the tool path, then the possible collision region is

$$y_L \leqslant E + \delta/2, \tag{14}$$

where $0 \leqslant E \leqslant \sqrt{R^2 + l_1^2}$, the more accurate value of E is related with cutter orientation in middle area.

The flow chart of avoiding collision in SM is shown in Fig.9.

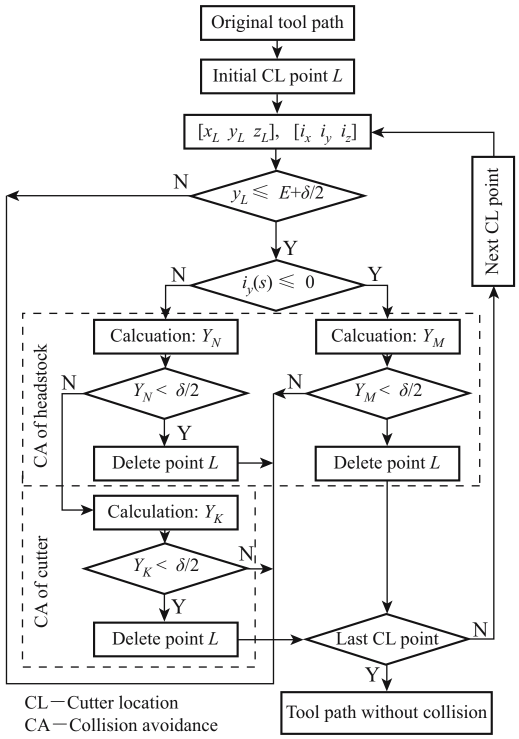


Fig.9 Flow of avoiding collision in SM

7 Application and analysis

As shown in Fig.10, a twin-skeg ship model surface is a symmetrical freeform surface with a size of 8000×1200×800 in mm. In order to improve the machining efficiency, the surface is machined by 4-axis symmetrical machining tool (see Fig.11). The parameters of symmetrical machining tool are R=100 mm, r=50 mm, l_1=350 mm, l_2=80 mm, δ=5 mm, and E=100 mm.

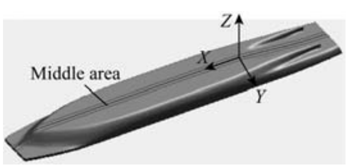


Fig.10 A twin-skeg ship model surface

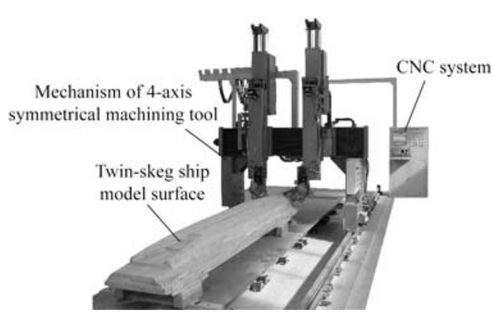


Fig.11 Four-axis symmetrical manufacturing tool

Due to the symmetrical machining, we only need to consider half of the ship model surface. The original tool path of the ship model surface is shown in Fig.12, and the machining simulation of the original path is shown in Fig.13. As shown in Fig.13, there is no machining residue in the middle area, indicating that the collision among cutters or headstocks would happen in the area. The tool path without collision is shown in Fig.14, and the machining simulation of the path is shown in Fig.15. As shown in Fig.15, there is a machining residue in the middle area, meaning that the collision among cutters or headstocks could be avoided[11].

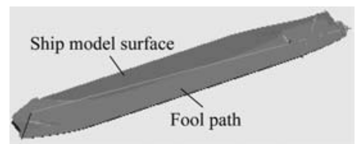


Fig.12 Original tool path of the ship model surface

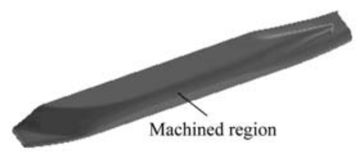


Fig.13 Machining simulation of the original tool path

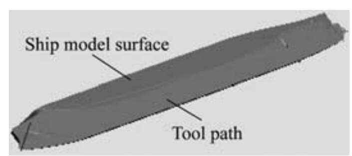


Fig.14 Tool path without collision

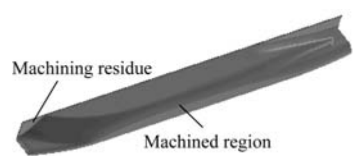


Fig.15 Machining simulation of the tool path without collision

The ship model surface after SM is shown in Fig.16. The real minimal width of the machining residue in middle area is 5.2 mm, which is slightly greater than δ (5 mm) because of the elastic deformation of wood in SM. So, based on the CAP concept, the above algorithm can avoid collision in SM and effectively control machining residue.

To make full use of the high efficiency of SM, we can control the area of machining residue (machined only by single cutter) to below 3% of the whole machined surface by setting the distance δ=5 mm. The practical machining results show that finishing the twin-skeg ship model surface needs at least 13 h for 4-axis NC machine tool with single cuter, while only 7 h are needed with 4-axis symmetrical machining tool. So the efficiency of the symmetrical machining tool is 85% higher than that of the traditional machine tool with single cutter.

Fig.16 A twin-skeg ship model surface after SM

8 Conclusion

Symmetrical machining can greatly improve machining efficiency of large symmetrical freeform surface. However, it introduces collisions among cutters or headstocks and machining residue. Based on the collision avoidance planes, we propose a collision avoidance algorithm. The algorithm has been shown to be practical by a real machining example. Although the collision avoidance algorithm is based on columnar headstock and flat cutter, it can be generalized into other kind of headstocks and cutters by rebuilding their models.

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