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Multi-point Clamping with Automatic Collision Avoidance for Aircraft Structural Parts Machining

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Abstract

In order to solve the problem of machining motion collision between cutter and fixtures, a multi-point clamping system with automatic collision avoidance is proposed for aircraft structural parts. The system is developed in consideration of part localization and modular clamping functions, and independent of CNC machine tools for the convenience of application. And then, a model-based collision detecting algorithm is designed, which can be implemented by comparing the cutter’s actual position extracted by ultrasonic sensors, and the calibrated positions of clamping points. Finally, a modular fixture system with automatic collision avoidance was manufactured and tested. From machining experiments, it indicates that the proposed fixture system can be highly efficient and very flexible to meet the aircraft structural parts machining requirements.

Keywords: Multi-point clamping; Automatic collision avoidance; Fixturing; Structural parts; Aircraft;

1. Introduction

With the rapid development of the aircraft manufacturing industry, the relevant machining equipment and approaches have already been the hot fields for the aircraft structural parts[1-3]. The beam frame part is one of the typical parts with the characteristics of structural complexity, low rigidity (thin-walled), high material removal rate and so on. These characteristics bring great challenges to machining. Generally, the machining process becomes more centralized and is desired to be completed within once clamping. Multi-point clamping is an efficient and practical approach to ensure the static and/or dynamic stability for these parts machining. However, it is always inevitable that

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some clamping points are very close to the machined features, such as slots, ribs, holes and so on. In such a situation, the tool path and posture planning may be disabled to solve the machining motion collision between cutter and clamping points. Actually, traditional multi-point fixture systems are usually manual and inefficient with repeated localization and clamping. Thus, it is a knotty problem for the aviation manufacturing industry.

One common collision avoidance way is that extra boss is reserved on the rough parts for clamping. However this way wastes many raw materials and increases the cost. In recent decades, many flexible fixture systems have been developed and applied to the aircraft structural parts machining[4, 5]. CNA Manufacturing Systems incorporated developed the POGO flexible tooling system that is a turnkey, automated, universal holding fixture used to rigidly hold contoured panels made of metal and/or composites for a variety of manufacturing operations[6]. The POGO system is typically integrated with a CNC machine tool or robot, creating a completely integrated, flexible manufacturing cell. M. Torres company developed the TORRESTOOL that is a flexible universal holding fixture specially designed to support in space aircraft structural components, while they are machined or laser cut[7]. The TORRESTOOL is a modular concept consisting on a number of carriages that move on the X-axis direction, with a number of supports per carriage, which move on the Y and on the Z axes.

In this research, as an alternative practical approach, a multi-point clamping and modular fixture system with automatic collision avoidance is developed. The proposed system can make the cutter move continuously by the ability of automatic collision avoidance, and improve the machining efficiency. The early-warning strategy by the ultrasonic sensors and the detailed collision avoidance method based on the artificial potential field model are proposed. Finally, the validity is tested in the machining experiments.

2. System design

2.1. Structure overview

In consideration of the features of beams frame parts and the flexibility of the process equipment system, some design rules should be observed as listed below,

- **Localization flexibility:** the system can adapt to complex parts with different specifications of structure and size.
- **Modularization:** the number and clamping positions of fixtures can be adjusted in different machining situations.
- **Fixture flexibility:** the force and position of the clamping point can both be changed based on the parts rigidity properties and the cutter planning.

As shown in Fig. 1, the clamping system is designed for the high-efficiency machining of the beams frame parts. It is mainly composed of the bottom board, fixtures, ultrasonic sensors, and tool setting gauge. The bottom board is fixed on the workbench of the CNC machine tool. The fixtures are positioned and fixed on the planned clamping points. Then the parts are put in the exact position and pressed firmly by the fixtures. The ultrasonic sensors are applied to on-line monitoring and position feedback of the cutter. The modular design of the fixture improves the machining flexibility and efficiency.

2.2. Fixture mechanism

The independent modular fixture system is more flexible than the specialized process equipment system. As shown in Fig. 1, the fixture module mainly includes the clamping rod, pressure head, air cylinder, and fixed plate. The clamping rod with two degrees of freedom can move up and down in the direction of Z-axis and rotate around the Z-axis. Thus, it has the ability of clamping the parts in different heights and avoiding collision. Furthermore, the clamping force with the maximum 7kN on the parts can be adjustable. The optimal clamping force is selected based on the FEA static analysis, which can make sure the local parts deformation in an acceptable range.

2.3. Localization

Six-point location principle is adopted for the parts localization to make sure the structural parts in the correct machining position and orientation. As shown in Fig. 1, the bottom board is fixed on the workbench by six pressing plates. Then the bottom plane of the parts is selected as the localization datum plane. The parts is placed on the support
plates to restrict the translational freedom in Z-axis, the rotational freedoms around X-axis and Y-axis. 2 mm deep groove is milled on the surface of the support plate. Then the translational freedom in Y-axis and the rotational freedom around Z-axis are restricted. The last translational freedom in X-axis is restricted by the pin and the hole. Through the above-mentioned approach, the parts can be localized stably.

Fig. 1. Fixture configuration for the beam frame part

3. Automatic collision avoidance method based on artificial potential field model

In order to realize the automatic collision avoidance and ensure machining precision and safety, the modular fixtures are controlled in several steps as shown in Fig. 2. In sum, the CNC machine tool works continuously and the relevant collision avoidance detection and control are started once the early-warning occurs.

3.1. Early-warning

As shown in Fig. 1, eight ultrasonic sensors on the bottom board can detect the cutter’s position in Z-axis and trigger early-warning. The sensors must be installed at some suitable positions in case that the potential collision
cannot be detected in time. The detection of the cutter’s position in Z-axis is realized by monitoring the height of the spindle. As shown in Fig. 3(a), the sensor installing distance \( d \) should satisfy the relation below,

\[
d \leq \sqrt{R^2 - \left(R_f + l_a + R_c\right)^2}
\]

where \( R, R_f, R_c \) and \( l_a \) denote the spindle radius, the diagonal length of the clamping rod, the cutter’s radius, and the horizontal safe distance, respectively. \( l_a \) is obtained from product of the maximum feed speed of the cutter and the maximum switching time of the fixture.

When the cutter is moved enough closely to the fixtures in different trajectories and the height of the spindle is lower than the early-warning height \( h_a \), different ultrasonic sensors may be triggered. As shown in Fig. 3(a), when the cutter moves along Trajectory 1, Ultrasonic sensor 2 and 4 will be triggered. When the cutter moves along Trajectory 2 that is close to parts edge, only Ultrasonic sensor 2 can be triggered. Once any ultrasonic sensor is triggered, the relevant fixtures will start the collision avoidance detection.

3.2. Automatic collision avoidance

Every fixture can be controlled independently to avoid the cutter. However, early-warning does not mean that the collision between the fixture and the cutter happens consequentially. In some cases, the cutter may just pass by the region but early-warning by the ultrasonic sensor is triggered. Therefore, a method based on artificial potential field model[8] is proposed in order to judge if the fixture starts to avoid, how the fixture avoids, and when the fixture resets.

As shown in Fig. 4(a), the fixture system is fixed onto the center of the workbench. When the cutter’s position \( O_c \) is \((0,0)\) in the tool machine coordinate system, the initial distances in the directions of \( X \)-axis and \( Y \)-axis detected by the sensors are \( d_{x0} \) and \( d_{y0} \). So \( O_c \) in the coordinate system of \( O-XYZ \) can be expressed as,

\[
O_c = (x_c, y_c, z_c)^T = (d_x - d_{x0}, d_y - d_{y0}, d_z)^T
\]

where \( d_x \), \( d_y \), and \( d_z \) are the detection distances by ultrasonic sensors in the directions of \( X \)-axis, \( Y \)-axis, and \( Z \)-axis, respectively.

After clamping points \( C_i (i=1,2,\cdots,n) \) are selected, the coordinates \( C_i = (x_i, y_i, z_i)^T \) are certain in \( O-XYZ \). The end point and rotational axis of the fixture \( i \) are denoted as \( O_i(x_i, y_i, z_i)^T \) and \( O'_i(x'_i, y'_i, z'_i)^T \) \((i=1,2,\cdots,n)\). The vector \( a_i \) is \((x_{ai}, y_{ai}, z_{ai})^T\).

The collision avoidance detection is implemented in two steps. The detection in the direction of \( Z \)-axis is firstly applied to judging if the cutter would indeed work closely to the clamping point. If \( z_c < h_a \) is true, it declares that the
cutter will be in the collision avoidance region and the detection in the horizontal plane should be started immediately. The horizontal detection should solve three problems as follows,

- If it is necessary for the fixture to avoid,
- The rotational direction of avoiding,
- When the fixture resets.

In order to solve these problems, the avoidance method is proposed based on artificial potential field. In the system, the clamping point, the cutter, and the fixture are regarded as the target point, the barrier, and the controlled object, respectively. Generally, the artificial potential field contains two aspects: the gravitational function and the repulsive function. However, only the repulsive function $F_{re}(O_f)$ is considered here and it can be obtained by,

$$F_{re}(O_f) = \begin{cases} 0, & \|O_f - O_i\| \geq R_s \\ \eta \frac{1}{\|O_f - O_i\| - \frac{1}{R_s}} \frac{O_f - O_i}{\|O_f - O_i\|}, & 0 \leq \|O_f - O_i\| < R_s \end{cases}$$

(3)

where $F_{re}(O_f)$, $\eta$, and $R_s$ denote the repulsive force, the repulsive constant and the safe radius as shown in Fig. 4(b), respectively.

Based on $F_{re}(O_f)$, the rotational speed $\theta$ of the fixture is controlled as,

$$\theta = \begin{cases} 0, & \|F_{re}(O_f)\| = 0 \\ \frac{\pi}{2} \left( F_{re}(O_f) = 0 \right) \cap \left( F_x \cdot y_w - F_y \cdot x_w \geq 0 \right), & -\pi/2 \left( F_{re}(O_f) = 0 \right) \cap \left( F_x \cdot y_w - F_y \cdot x_w < 0 \right) \end{cases}$$

(4)

where $\omega_m$ is the maximum rotational speed.

The algorithm and the control system are implemented on the industrial computer that is completely independent of the CNC system. Based on Eq. (4), once the cutter steps into the safety area as shown in Fig. 4(b), the fixture will be turned to the opposite side. After the cutter leaves, the fixture will reset and press onto the parts again.

![Fig. 4 Avoidance model](image)

4. Experiment verification

In order to verify the validity of the proposed fixture system, an aluminum alloy structural frame with the size of 560mm×110mm×16mm is tested, on which the grids for weight reduction should be machined. Based on the FEA analysis results, four fixtures are selected to fix the parts and the clamping force of each fixture is 370N. The diameter of milling cutter is 10mm. The spindle speed is 2000rpm. As shown in Fig. 5(a), the four fixtures are controlled
simultaneously to press onto the frame parts. As shown in Fig. 5(b), the cutter moves closely to the fixture from the right side. The clamping rod of the fixture rotates left immediately and succeeds to avoid the cutter. After the cutter leaves away, the clamping rod resets quickly as shown in Fig. 5(c). When the machining is finished, all the four fixtures raises up simultaneously. Fig. 5(d) shows the machined parts.

The experiment results prove that the proposed fixture system with automatic collision avoidance can realize the avoiding of the cutter and the continuous work of the CNC machine tool. The machining efficiency increases by at least 30%.

![Fig. 5 Machining experiments](image)

5. Conclusion

In this paper, a modular fixture system with automatic collision avoidance is proposed for the high-efficiency machining of the beams aircraft frame parts. The automatic collision avoidance control method is proposed based on the artificial potential field. The experiment results indicate that the proposed fixture system can be applied to the high-efficiency machining of beams frame parts, and realize the continuous work of the CNC machine tool by avoiding the cutter movement collision actively.

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