Research on tool path generation for integrated off-axis four-mirror group in single point diamond turning

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Abstract. Multi-free-surface mirror integrated system is the development trend of optical system, but its ultra-precision machining is very difficult, this paper mainly studies the tool path generation problem of multi-free-surface reflector integrated system. In this paper, two tool path generation methods for the off-axis four-mirror group machining with SPDT are presented, one tool path generation method is separate machining and the other is integrated machining. Both methods are based on cylindrical spiral and generate tool path by projecting points onto surfaces. For the tool path generation method of integrated machining, the linear transition is used to realize the smooth transition of the mirror surfaces. By comparing the simulation machining of two kinds of tool path generating methods, it is found that the integrated tool path generating method is more suitable for off-axis four-mirror group machining and has higher machining efficiency.

1. Introduction
Ultra-precision machining is a very promising method, which can provide high efficiency, high flexibility, and low cost for creating the high quality surface with achievable sub-micrometric form accuracy and nanometric surface roughness [1], such as off-axis aspheric surfaces. The off-axis four-mirror group is a free-form surface group composed of several off-axis aspheric surfaces, which is very popular in airborne field.

At present, there are many researches from various aspects about ultra-precision manufacturing, and most of them have achieved great improvement [2-4]. Because tool path generation is an important part of ultra-precision machining, a lot of researches on tool path generation methods have been carried out in recent years. Khaghani, A etc. proposed an innovative approach to tool path generation for ultra-precision machining of freeform optic surfaces based on the principle of Automatic Dynamics Analysis of Mechanical Groups, generated the tool path for very complex freeform surfaces [5]. Liu, YZ etc. proposed a partition method for T-spline surface based on its flexible topology and face-by-face sampling, which improved the partition efficiency [6]. Fountas, NA etc. dealt with an original approach of globally optimizing tool paths to CNC-machine sculptured surfaces [7]. Nevertheless, there are few researches on tool path generation for multi-free-surface group manufacturing. At present, more and more attentions are paid to the global optimization of multi-free-surface group. Therefore, it is necessary to propose a tool path generation method for integrated machining of the off-axis four-mirror group.
In this paper, two tool path generation methods for the off-axis four-mirror group machining with SPDT are presented. This paper gives a detailed introduction of the tool path generation process of these two methods, and simulates the machining of the two tool paths by using MATLAB software, and compares the machining efficiency of the two methods.

2. Design of the off-axis four-mirror group

The off-axis four-mirror group can make the optical group obtain a larger imaging field of view and make the group structure more compact. Based on Zernike free-form polynomial, four aspheric free-form surfaces (M1-M4 surface) are designed and combined into an off-axis four-mirror group, as shown in Fig.1. The expression of Zernike polynomial is:

\[ z = \frac{c(x^2 + y^2)}{1 + \sqrt{1 - (1+k)c^2(x^2 + y^2)}} + \sum_{m,n} C_{m,n} x^m y^n \]  

(1)

Where \(1/c\) is the Y radius, \(k\) is the conic constant, \(C_{m,n}\) is the coefficients for \(x^m y^n\).

3. Tool path generation for separate machining

The first method is to process each surface in the off-axis four-mirror group separately. The path of tool contact points is generated by projecting the points on a cylindrical spiral tool path onto the surfaces. So first of all, we should to generate a cylindrical spiral tool path which tangent to the point closest to the axis in the off-axis four-mirror group. The expression of the cylindrical spiral is:

\[
\begin{align*}
    y &= \rho \cdot \cos \theta \\
    z &= \rho \cdot \cos \theta \\
    x &= x
\end{align*}
\]

(2)

where \(\rho\) is the radius of the cylindrical spiral tool path, \(\theta\) is the angle of each point on the cylindrical spiral tool path.

Then the points on the cylinder helix can be projected onto the surface (M1-M4 surface), and the tool path of each mirror processing is shown in Fig.2:
Figure 2. Tool path generation for separate machining of the off-axis four-mirror group: (a) M1 tool path generation; (b) M2 tool path generation; (c) M3 tool path generation; (d) M4 tool path generation; (e) the off-axis four-mirror group tool path generation.

In this paper, MATLAB software was used to simulate the machining of the off-axis four-mirror group with the separate machining method, and the machining time of tool path generated by different kinds of pitch are obtained, as shown in Table 1. Supposed the cutting speed is \( v = 40 \text{mm/s} \) and the no-load speed is \( v' = 200 \text{mm/s} \). In this paper, six kinds of pitch are set for tool path generation to simulate the cutting time of the off-axis four-mirror group. The six kinds of pitch are set as 0.05mm, 0.06mm, 0.08mm, 0.10mm, 0.12mm, 0.15mm.

Table 1. The processing time of the off-axis four-mirror group with the separate machining method.

| Group number | M1 processing time [s] | M2 processing time [s] | M3 processing time [s] | M4 processing time [s] | Total processing time [s] |
|--------------|------------------------|------------------------|------------------------|------------------------|--------------------------|
| 1            | 6.5492×10^4           | 3.2953×10^4           | 3.4763×10^4           | 4.4283×10^4           | 1.7749×10^5 s            |
| 2            | 5.6181×10^4           | 2.5245×10^4           | 2.8969×10^4           | 3.6907×10^4           | 1.4730×10^5 s            |
| 3            | 4.0930×10^4           | 1.8933×10^4           | 2.1726×10^4           | 2.7680×10^4           | 1.0927×10^5 s            |
| 4            | 3.2742×10^4           | 1.5146×10^4           | 1.7379×10^4           | 2.2144×10^4           | 8.7441×10^4 s            |
| 5            | 2.7283×10^4           | 1.2621×10^4           | 1.4482×10^4           | 1.8450×10^4           | 7.2836×10^4 s            |
| 6            | 2.1825×10^4           | 1.0096×10^4           | 1.1585×10^4           | 1.4760×10^4           | 5.8266×10^4 s            |

4. Tool path generation for integrated machining

Same as to the first method, the integrated machining method of the off-axis four-mirror group also need to project the points on a cylindrical spiral tool path onto each surface to obtain the overall and continuous tool path. The cylindrical spiral tool path generated in the off-axis four-mirror group tangent to the nearest point off the axis is shown in Fig.3:

Figure 3. The cylindrical spiral tool path generation

Then, according to the angle range of each surface in the off-axis four-mirror group, the points on the cylinder spiral in this range are projected onto the surfaces. In order to ensure the processing quality of surface boundary in the group, the tool path on the surface boundary is widened to generate a transition zone [9], as shown in Fig.4:

Figure 4. The tool path generation for integrated machining

However the generated tool path is not smooth between the cylinder surface and the off-axis four-mirror group surface, as shown in Fig.4. In this case, during the actual processing, the machine tool will produce a large acceleration change, resulting in the vibration of the machine tool and even cause the machine tool to stop. Therefore, it is necessary to process the tool path of the transition between the surfaces of the off-axis four-mirror group, so as to realize the smooth transition.
Figure 5. The principle of tool path transition between surfaces of the off-axis four-mirror group

The principle of tool path transition between surfaces of the off-axis four-mirror group is shown in Fig.5. Because the start points \( P_{st} \) and end points \( P_{end} \) of the transition tool path are on the surface of the Off-axis four-mirror group. So the coordinates of these two points \( P_{st}(x_{st}, y_{st}, z_{st}) \) and \( P_{end}(x_{end}, y_{end}, z_{end}) \) can be obtained according the Eq.1. The transition line between surfaces is:

\[
\frac{x - x_{st}}{x_{end} - x_{st}} = \frac{y - y_{st}}{y_{end} - y_{st}} = \frac{z - z_{st}}{z_{end} - z_{st}}
\]

(3)

The points \( P_i'(x_i', y_i', z_i') \) on the cylindrical spiral can be projected onto the transition lines in the direction of radius to obtain the point \( P_i(x_i, y_i, z_i) \):

\[
\begin{align*}
x_i &= x_i' \\
y_i &= \rho_i \cdot \cos \theta_i \\
z_i &= \rho_i \cdot \sin \theta_i
\end{align*}
\]

(4)

where \( \theta = \theta_i' \). Substitute Eq.4 into Eq.3 to calculate the radius \( \rho_i \) of projection points on the transition line. Then according to Eq.4 can get the coordinates of the point \( P_i(x_i, y_i, z_i) \) and the smooth transition between the surfaces of the off-axis four-mirror group can be completed.

Figure 6. The smooth transition tool path generation for integrated machining of the off-axis four-mirror group
Figure 7. The simulation processing time of the two methods

Similar to the first method, this paper also simulates simulate the machining of the off-axis four-mirror group with the integrated machining method, and sets the same kinds of pitch to generate tool path. The specific simulation machining time is shown in Table 2:

Table 2. The processing time of the off-axis four-mirror group with the separate machining method.

| Group number | M1 processing time [s] | M2 processing time [s] | M3 processing time [s] | M4 processing time [s] | Total processing time [s] |
|--------------|------------------------|------------------------|------------------------|------------------------|--------------------------|
| 1            | 4.9138×10^4           | 1.6713×10^4           | 1.9628×10^4           | 3.1194×10^4           | 1.2817×10^5              |
| 2            | 4.0949×10^4           | 1.3926×10^4           | 1.6357×10^4           | 2.6009×10^4           | 1.0682×10^5              |
| 3            | 3.0712×10^4           | 1.0442×10^4           | 1.2268×10^4           | 1.9509×10^4           | 8.0118×10^4              |
| 4            | 2.4569×10^4           | 8.3513×10^3           | 9.8141×10^3           | 1.5607×10^4           | 6.4092×10^4              |
| 5            | 2.0474×10^4           | 6.9577×10^3           | 8.1784×10^3           | 1.2999×10^4           | 5.3402×10^4              |
| 6            | 1.6379×10^4           | 5.5642×10^3           | 6.5427×10^3           | 1.0402×10^4           | 4.2721×10^4              |

5. Analysis of two tool path generation methods

The simulation processing time of the two methods is compared in Fig.8. It can be seen from Fig.8 that the integrated processing method of off-axis four-mirror group takes less time and has higher processing efficiency than the separate processing method. Therefore, the tool path generation method of integrated machining is more suitable for off-axis four-mirror group machining.

6. Conclusion

This paper introduces two kinds of tool path generation methods for off-axis four-mirror group machining. For the tool path generation method of integrated machining, a linear transition method is adopted to realize the smooth transition of tool path between the mirror surfaces, which is suitable for SPDT of slow tool servo. This paper also compares the processing time of the two methods, and concludes that the integrated tool path generation method has short processing time. Therefore, the tool path generation method of integrated machining studied in this paper can be applied to the machining of off-axis four-mirror group and improve the machining efficiency.

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