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To cite this article: Yang Zhuojuan et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 392 062046

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The Influence of Installation Error on the Motion of Spatial Cam Mechanism and Its Simulation

Yang Zhuojuan  Liu Wencheng  Duan Xiumin

No. 3050 Kaixuan Road, Kuancheng District, Changchun City, Jilin Province
JILIN ENGINEERING NORMAL UNIVERSITY  Mechanical Engineering Institute

Abstract. In this paper, taking the camber indexing cam mechanism as an example, the mathematical model of the space cam mechanism motion is established. The influence law of the installation error on the meshing line deviation and the angular displacement error of the cam mechanism is examined. And then the effective suggestion for the error control is proposed.

1. Introduction

The space cam mechanism is widely used in automatic feed and some automated processing equipment because of its small size, high speed, and high precision. Due to the complexity of three-dimensional models and their motion analysis, the research in this area is rare [1–4]. Due to the errors in the installation and manufacturing process, coupled with the high-speed operating conditions of the cam, the wear between the conventional cylindrical roller and the convex contour surface, especially the wear caused by the corner impact is often prominent. In order to prevent the wear, an improved drum-type roller follower [5] can generally be used. In this paper, an improved drum-roller cambered indexing cam mechanism is taken as the object of study. The effect of installation error on the movement of the cam mechanism is quantitatively examined.

2. The mathematical model of the spatial cam mechanism

As shown in Fig. 1, there are three coordinate systems: a coordinate system that rotates with the indexing plate $O_1 - X_1 Y_1 Z_1$; a coordinate system that rotates with the cam $O_2 - X_2 Y_2 Z_2$; a fixed coordinate system $O_3 - X_3 Y_3 Z_3$.

In $O_1 - X_1 Y_1 Z_1$, if the conventional cylindrical roller follower is modified to a drum type, the parametric equation of the curved surface can be rewritten as follows. Fig. 2.

\[
\begin{align*}
    x_1 &= L' + R' \sin \mu \\
    y_1 &= (R' - \gamma_{\max} - R' \cos u) \cos \rho \\
    z_1 &= (R' - \gamma_{\max} - R' \cos u) \sin \rho
\end{align*}
\]

Where $\rho$ stands for improved drum roller contact angle, $0 \leq \rho \leq 2\pi$

- $R'$ - Improved drum-type roller radius of curvature
- $L'$ - The distance between the highest point of the drum roll and the centre of the indexing disk
- $\mu$ - Improved surface parameters of drum-type roller followers

And $\sin^{-1} \left( \frac{(L_{\min} - L')}{R} \right) \leq \mu \leq \left( \frac{L_{\min} - L'}{R} \right)
Fig. 1 The establishment of the coordinate system of the space cam mechanism

Figure 2 Improved drum roller geometry

In $O_2-X_2Y_2Z_2$, From the knowledge of the spatial meshing principle and differential geometry, the contour surface equation can be derived as:

$$
\begin{align*}
x_2 &= L \cos f \cos \phi + r(\sin f \cos \theta \cos \phi + \sin \theta \sin \phi) - a \cos \phi \\
y_2 &= -L \cos f \sin \phi - r(\sin f \cos \theta \cos \phi + \sin \theta \cos \phi) + a \sin \phi \\
z_2 &= L \sin f - r \cos \theta \cos f
\end{align*}
$$

Where $f$ - Angular displacement function, $r$ - Cylindrical roller radius, $L$ - Cylindrical roller follower surface parameters, $\theta$ - Cylindrical roller follower surface parameters,

$$
\theta = \tan^{-1}\left[\frac{L}{\sqrt{(x - L \cos f) \cdot df/d\phi}}\right], \quad a - \text{Middle distance}.
$$

3. Determination of Engagement Surface Equation of Cam Mechanism Considering Error

In order to quantitatively describe the meshing state of the cam, it is assumed that the relative positions of the two meshing surfaces are known. With an improved drum-type roller cam follower as an example, when there is an installation manufacturing error, a cam and follower surface contact analysis (SCA) model is established.

In $O_2-X_2Y_2Z_2$, Convex surface equation transformation to a fixed coordinate system $O_3-X_3Y_3Z_3$, (2) Multiply the transformation matrix
\[
M_{32} = \begin{bmatrix}
\cos \phi & -\sin \phi & 0 & 0 \\
\sin \phi & \cos \phi & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Where \( \phi \) - Corner from \( X_2 \) axis to \( X_3 \) axis

In \( O_3 \cdot X_3Y_3Z_3 \), Consider the disturbance of the cam along the \( X_3 \), \( Y_3 \), \( Z_3 \) direction \( \delta_x \), \( \delta_y \), \( \delta_z \), the convex profile equation is:

\[
\Sigma_3 = M_{32} = \begin{bmatrix}
x_3 \\
y_3 \\
z_3 \\
1
\end{bmatrix} = \begin{bmatrix}
x_1 \\
y_1 \\
z_1 \\
1
\end{bmatrix} + \begin{bmatrix}
\delta_x \\
\delta_y \\
\delta_z \\
0
\end{bmatrix}
\]

(3)

Same reason, In \( O_3 \cdot X_3Y_3Z_3 \), Consider the disturbance of the cam along the \( X_3 \), \( Y_3 \) direction \( \delta_x \), \( \delta_y \), the convex profile equation is:

\[
\Sigma_3' = M_f \Sigma_3
\]

(4)

Where

\[
M_f = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & \cos(-\delta_y) & \sin(-\delta_y) & 0 \\
0 & -\sin(-\delta_y) & \cos(-\delta_y) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
M_{r_3} = \begin{bmatrix}
\cos(-\delta_x) & 0 & -\sin(-\delta_x) & 0 \\
0 & 1 & 0 & 0 \\
\sin(-\delta_x) & 0 & \cos(-\delta_x) & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

In \( O_3 \cdot X_3Y_3Z_3 \), If the indexing coiling \( Z \)-axis error \( \delta_{r_3} \) exists, the improved drum roller follower expansion equation is:

\[
\Sigma_3'' = M_{33} M_f \Sigma_3
\]

(5)

Where

\[
M_{33} = \begin{bmatrix}
1 & 0 & 0 & -a \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

\[
M_{r_3} = \begin{bmatrix}
\cos(-\delta_x) & \sin(-\delta_x) & 0 & 0 \\
-\sin(-\delta_x) & \cos(-\delta_x) & 0 & 0 \\
0 & 1 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]
\[ \Sigma_{y_f} = \begin{bmatrix} L \cos \delta + R' \sin \cos \delta + h \sin \delta \cos \rho \sin \rho \\ L' \sin \delta + R' \sin u \sin \delta - h \cos \delta \cos \delta \\ 1 \end{bmatrix} = \begin{bmatrix} x_s \\ y_s \\ z_s \\ 1 \end{bmatrix} \]

Because the convex contour surface and the improved roller follower profile are continuous tangent, that is to say, in the fixed coordinate system, the position vector and the normal vector of the two surface equations at any point in time must be the same. This is the space contact condition when the cam is operating. The surface contact analysis method (SCA) can be used to accurately calculate the misalignment and angular displacement errors of the cam due to mounting errors [5].

4. Calculation Examples

The sinusoidal curve is selected as the angular displacement function for calculating the above-mentioned error, and it is a DRRD (stop - liter - drop - stop) type curve. It includes the entire working cycle. The main parameters are shown in Table 1.

Assume that the cam rotation range is between 30° and 330°, the follower swing angle is 45°, and the initial value of the angular displacement function \( f(\phi) \) is -22.5°, and when \( L = 55 \), the meshing line of the cylindrical roller is the ideal meshing path. The other data of the cam mechanism is shown in Table 1.

| \( A \) | Unit (mm) |
|---|---|
| \( \gamma \) | \( \gamma_{\text{max}} \) | \( L_{\text{min}} \) | \( L_{\text{max}} \) | \( L \) | \( R \) | \( L' \) |
| 100 | 8 | 8 | 50 | 62 | 55 | 500 | 55 |

The result of the calculation is shown in Figure 3 and Figure 4. The relationship between the cam angle and the amount of misalignment of the mesh is shown in Fig. 3 (a) (b) when the three components \( (\delta_x, \delta_y, \delta_z) \) of the transmission error are 0.1 mm. From Fig. 3, it can be seen that the misalignment caused by the transmission error is about from 0.246 mm to 0.480 mm, while the displacement error is about 0.0398 mm. The result of meshing line offset is approximately 0.520 mm caused by \( \delta_y \). And the displacement error caused by \( \delta_z \) is smaller.
Fig. 3(a) Relationship between cam angle and meshing line deviation
(b) Relationship between cam angle and displacement deviation

Fig. 4(a) Relationship between cam angle and meshing line deviation
(b) Relationship between cam angle and displacement deviation

Fig. 4 shows that the axial rotation angle error $\delta_x$ and $\delta_y$ have a small effect on the displacement error and the mesh line deviation. From Fig. 3 and Fig. 4, it can also be seen that the influence of the assembly error in the six directions on the actual meshing line is similar to that of the displacement error. Each displacement error curve is also similar to its corresponding meshing line and is basically anti-symmetric with its penetration axis. This characteristic is often regarded as an important indicator of the accuracy of the cam mechanism. By detecting the actual meshing line on the cam surface, it can be determined whether the cam mechanism is installed accurately.
5. Conclusion
From the above discussion, we can see that when installing the roller gear cam mechanism, the assembly error $\delta_y$ and $\delta_y^\gamma$ should be as small as possible in order to avoid the large displacement error and actual meshing deviation. However, $\delta_x$, $\delta_y^\gamma$, $\delta_y^\gamma$ have little effect on the influence of the displacement error, which mainly because the meshing line is closer to the ideal meshing line with the smallest deviation.

Acknowledgements
This work is supported by Program for Innovative Research Team of Jilin Engineering Normal University.

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