Research on Taper Detection Method of Roller for Belt Conveyor

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Abstract. The taper of the roller's body is closely related to the self-correcting efficiency of belt deviation and the reliability of roller operation on belt conveyor. Due to the installation structure of roller, it is difficult to evaluate the taper of roller by manual multi-point detection and comprehensive analysis. In this paper, the taper correlation index is defined based on outer cylindrical surface of roller and designed the automatic detection method. The error processing model of data is established according to actual tooling conditions for testing and the realization scheme of sensor detection. The feasibility of the design method is verified by testing the standard roller.

1. Introduction

The belt conveyor is often composed of a combination of a main driving roller and a plurality of driven rollers. The belt runs quickly under the tension and friction provided by the roller distribution structure. As the basic mechanical structural component necessary in the belt conveyor, the outer surface of the roller is generally processed into a cone-shaped cylinder surface. The middle cylinder bears the maximum belt tensioning force, and the belt tension on both sides of the cone-column section is relatively small to provide the centering force when the belt is running. Thereby reducing the risk of belt deviation and the risk of downtime caused by belt edge wear [1~3]. Obviously, the relevant quality parameter control of the roller is an important guarantee for the normal production of the belt conveyor.

The evaluation of roller taper must be related to the axis of the roller. However, the roller in the application is deviated from the center of the bearing or the center of the support surface, and the actual axis deviates from the theoretical axis. It is not feasible to rely on manual selection of static geometry to measure the roller taper. It is not feasible to rely on manual selection of static acquisition related geometric quantities for roller taper evaluation in the sampling or full inspection requirements of mass production of rolls. Because the method is inefficient and the credibility of the results is more difficult to guarantee. In this paper, with the aim of high efficiency and appropriate detection accuracy, the roller taper detection realization scheme is designed for the actual roller products.
2. Detection method design

2.1. Roller taper definition
In combination with the actual production, it is assumed that the clamping tooling and processing equipment during the processing of seamless steel tubes have ideal conditions. Each axial section of the roller is a standard circle, and the cylinder surface can be used as a reference to form a circular center line of each cutting surface. The axis is called the theoretical axis. After the shaft support surface is added on both sides of the roller, the axial ends of the two end faces are connected, which is called the actual axis. Therefore, the deviation between the theoretical axis of the roller and the realization of the axis is called the off-axis error. Subsequent detection methods are designed according to the off-axis definition.

The roller cylinder is divided into three sections, the front and rear a and c sections are cone sections, and the middle section b is a cylindrical section. The taper is the taper $C$ of the two segments a and c based on the theoretical axis.

\[ C = \frac{z_2 - z_1}{2t} \]  

For example, the taper of the two sections a and c is strictly consistent and is center-symmetrical.

2.2. Column radius measurement

2.2.1. Calculate the length of the roller: $L(\beta) = L_n(\beta) - L_0(\beta)$. The theoretical radius of $l$-position roller is calculated by specifying in advance:

\[ r_l(\beta) = z_l(\beta) - w_l(\beta), (\beta = 0^\circ - 360^\circ) \]

2.2.2. The two-dimensional coordinate system is established with the theoretical axis as the origin $O(0,0)$. As shown in Fig.2, the measurement is performed under the actual axial support. The coordinates $P(x_j, y_j)$ of each sampling point on the $l_i$-position radial circular section are obtained, and the center $E(x, y)$ is fitted, and the roller radius of $l_i$-positions is calculated:

\[ \bar{r_i} = \frac{\sum^n_j \sqrt{(x-x_j)^2 + (y-y_j)^2}}{n} \]

If $A(x_1, y_1), B(x_2, y_2), C(x_3, y_3)$ are selected on a section circle, the calculation formula for the center of the circle is as follows:
\begin{align}
    x &= \frac{(y_2-y_1)(y_2-y_1+x_1-x_2)-(y_1-y_1)(y_1-y_1+x_1-x_2)}{2(x_1-x_2)(y_1-y_1)} \\
    y &= \frac{(x_2-x_1)(x_2-x_1+y_1-y_2)-(x_1-x_1)(x_1-x_1+y_1-y_2)}{2(y_1-y_1)(x_1-x_1)}
\end{align}

(3)

(4)

2.3. Column length measurement

By judging that the \( w_i(\beta) \) distinguishes the lengths of the three segments a, b, and c shown in Fig.1, the lengths of the cylindrical section and the cone section are obtained:

\[
\begin{align*}
    l_a(\beta) &= l_1(\beta) - l_0(\beta), w_i(\beta) > w_{i+1}(\beta), 0 \leq l < \frac{1}{2} n \\
    l_b(\beta) &= l_2(\beta) - l_1(\beta), w_i(\beta) = w_{i+1}(\beta), 0 \leq l \leq n \\
    l_c(\beta) &= l_n(\beta) - l_2(\beta), w_i(\beta) < w_{i+1}(\beta), \frac{1}{2} n \leq l \leq n
\end{align*}
\]

(5)

2.4. Cone section symmetry

After measuring the theoretical radius \( r_i(\beta) \) of the end faces on both sides of the roller, the eccentricity at both ends is taken as the evaluation index of coaxiality, expressed as:

Left side: \( \Delta r_{l_0} (\beta) = r_{l_1} (\beta) - r_{l_0} \Delta r_{l_0} = \frac{1}{n} \sum_{i=1}^{n} \Delta r_{l_0} (\beta) \)

(6)

Right side: \( \Delta r_{l_n} (\beta) = r_{l_n} (\beta) - r_{l_n} \Delta r_{l_n} = \frac{1}{n} \sum_{i=1}^{n} \Delta r_{l_n} (\beta) \)

(7)

Two-dimensional data \( M \left( l_i (\beta), w_i (\beta) \right) \) were processed by taper formula, so as to obtain taper C of roller cone column segment:

Left side: \( C_a (\beta) = \frac{w_{l_1} - w_{l_2}}{l_a}, C_a = \frac{1}{n} \sum_{i=1}^{n} C_a (\beta) \)

(8)

Right side: \( C_c (\beta) = \frac{w_{l_n} - w_{l_2}}{l_c}, C_c = \frac{1}{n} \sum_{i=1}^{n} C_c (\beta) \)

(9)

3. Error analysis and processing

3.1. Straightness error

There is certain deformation of ball screw guide, the straightness should be detected. In this paper, table marking method is adopted to measure the straightness of guide rail with the aid of standard precision ruler, and the linear equation coefficient is calculated by connecting the end points of head and tail as the initial value [7]:

\[
    q_i = \frac{z_i - z_0}{x_i - x_0}
\]

(10)

In the formula, the starting point \( D_0 (x_0, z_0) \); the end point \( D_n (x_n, z_n) \).

Transform to the new coordinates: \( D_i (x_i, d_i) \). Where: \( d_i = z_i - z_0 - q_i x_i \). Find the maximum deviation point \( D_{\max} (x_{d_{\max}}, d_{\max}) \) and the minimum deviation point \( D_{\min} (x_{d_{\min}}, d_{\min}) \) in \( d_i \).

\[
    K_{1i} = \frac{|d_{\max} - d_i|}{x_{d_{\max}} - x_i}
\]

(11)

\[
    K_{2i} = \frac{|d_{\min} - d_i|}{x_{d_{\min}} - x_i}
\]

(12)
The minimum values $K_{1j}$, $K_{2h}$ in $K_{1i}$, $K_{2i}$ were respectively calculated by formulas (11) and (12), and the coordinate values $D_j(x_j, d_j)$, $D_h(x_h, d_h)$ were obtained. Three poles: $D_{\text{max}}(x_{\text{max}}, d_{\text{max}})$, $D_{\text{min}}(x_{\text{min}}, d_{\text{min}})$ and $\{D_j(x_j, d_j) \mid K_{1j} < K_{2h}, D_h(x_h, d_h), K_{1j} > K_{2h}\}$. Calculate the straightness error $f_{mx}$ after reordering.

Left pole: $D_L(x_L, z_L)$; Intermediate pole: $D_M(x_M, z_M)$; Right pole: $D_R(x_R, z_R)$.

$$f_{mx} = \left| \frac{x_M-x_R}{x_R-x_L}(z_R-z_L) - (z_M-z_R) \right| \quad (13)$$

3.2. Spindle rotation error and roundness error

In the process of using the machine tool, the spindle rotation error exists. Since the axis cannot be measured directly, it is necessary to measure the deviation indirectly with the help of standard cylinder. However, this will bring the roundness error of the standard axis itself [5]. Therefore, in this paper, roundness error and spindle rotation error are separated by means of standard cylindrical rod by means of multi-step method [6]. The spindle of the machine tool drives the standard cylinder to rotate once, that is, each rotation angle $\theta = \frac{2\pi}{n}$. Due to the strict periodicity of roundness error, the corresponding fundamental and harmonious frequencies cancel each other when the data are added at all equal points on the whole week, i.e.,[8~11]:

$$\sum_{k=1}^{n} S_k(\theta) = 0 \quad (14)$$

$$V_k(\theta) = S(\theta + \frac{2\pi}{n} \cdot k) + r(\theta) \quad (15)$$

When the nth step is rotated, it coincides with the first sampling point, and the roundness error is zero [8]. Therefore, the rotation error and the roundness error are respectively:

$$r(\theta) = \frac{1}{n} \sum_{k=1}^{n} V_k(\theta) \quad (16)$$

$$S(\theta) = r(\theta) - V_0(\theta) \quad (17)$$

(Rotational error: $r(\theta)$; roundness error: $S(\theta)$; sensor measurement: $V_k(\theta)$; measurement point position: $\theta$).

3.3. Parallelism error

During the installation process, the scale is not guaranteed to be completely parallel to the theoretical axis of the drum. This also causes the planes where the two are located to intersect somewhere in the space, which causes the parallelism error [4]. The plane where the theoretical axis lies and intersects the horizontal plane is called the reference plane. And the plane where the grating is located and intersects with the horizontal plane is called the plane. Let the measured points of the actual measured plane and the actual reference plane be $M_i(x_i, y_i, z_i)$ and $G_j(x_j, y_j, z_j)$ respectively. The actual datum plane equation is:

$$\begin{vmatrix} x-x_1 & y-y_1 & z-z_1 \\ x_2-x_1 & y_2-y_1 & z_2-z_1 \\ x_4-x_3 & y_4-y_3 & z_4-z_3 \end{vmatrix} = 0 \quad (18)$$

After equation (18) is expanded according to the first row, the coefficients of $x$, $y$, and $z$ are respectively $A$, $B$, and $C$. The constant term is $D$. The equation of the reference plane is expressed as:
Ax + By + Cz + D = 0  \hspace{1cm} (19)

Therefore, the equations of the two parallel planes parallel to the reference plane and containing the actual measured plane are as follows:

\[ Ax + By + Cz + D_1 = 0 \]  \hspace{1cm} (20)

\[ Ax + By + Cz + D_2 = 0 \]  \hspace{1cm} (21)

According to the criterion for judging the minimum region of the face-to-face parallelism orientation, the coordinates of the high pole \(M_1(X_1, Y_1, Z_1)\) and the low pole \(M_2(X_2, Y_2, Z_2)\) in the actual measured plane points were substituted into equations (20) and (21), and the values of \(D_1\) and \(D_2\) were obtained. Therefore, the normal distance between the two parallel inclusion planes (width of the orientation minimum region) is the parallelism error \(f_N\), which can be calculated as follows:

\[ f_N = \frac{|D_1 - D_2|}{\sqrt{A^2 + B^2 + C^2}} \]  \hspace{1cm} (22)

4. Experimental verification

In this paper, the CA6140 model metal cutting machine tool is adopted, and the roller is fixed by the thimble on both sides of the machine to ensure the parallelism of the sensor detection. At the same time, the Keyence IL-100 laser displacement sensor (range 75~130mm, resolution 2μm), grating scale (range 1500mm, resolution 5μm) were selected for testing. The test roller size table is shown in Table 1:

| Roller model | Length | Length tolerance | Diameter | Diameter tolerance | Taper | Taper tolerance | Concentricity | Coaxial tolerance |
|--------------|--------|------------------|----------|-------------------|-------|----------------|---------------|------------------|
| Roller 65    | 1200 mm| ±0.5 mm          | 65 mm    | ±0.3 mm           | 0°    | 1:132~1:100    | 0 mm          | ±0.3 mm          |

Three rolls of model 65 were tested. The initial test results are shown in the following Table 2:

| model  | Center of mind | Length  | Diameter | Taper | Concentricity |
|--------|----------------|---------|----------|-------|---------------|
| 6501   | (-0.0603, -0.0034) | 1199.898 mm | 64.448 mm | 1:1372 | 0.15475 mm |
| 6502   | (-0.0468, 0.0295)  | 1200.327 mm | 64.174 mm | 1:1283 | 0.10638 mm |
| 6503   | (0.0471, 0.0687)   | 1200.433 mm | 64.534 mm | 1:1256 | 0.12557 mm |

Figure 2. Schematic Diagram of the actual radius of each sampling point of the 6502 roller
It can be seen from the data in the table that the diameter of the roller does not meet the tolerance requirements. It can be seen from Fig.2 that the radius of the cutting plane of each sampling point of the roller differs greatly from the standard radius, and the residual processing is required. The figure below shows the straightness error curve:

![Figure 3. Error Curve](image)

The straightness error formula is used to calculate the following Table 3.

The error curve formula is calculated by MATLAB software: $y = -0.0001x^2 + 0.0068x + 0.6274$. The roundness error and the rotation error are calculated to be equal to zero. Parallelism error calculation: $M_1(92.558,0,682.569) \ M_2(91.602,0,7.9833)$ parallelism error: $f_N = 1.351988\text{mm}$. After replenishing the above rollers, the following Table 4 is recalculated.

After the replenishment is completed, the diameters of the three rollers are within the tolerance range. It can also be seen from Fig.4 that after the replenishment is completed, the radius of the cut surface of each sampling point of the roller is close to the theoretical radius.

### Table 3. Straightness error calculation table

| $(x_0, z_0)$ | $(x_n, z_n)$ | Maximum deviation point | Minimum deviation point | $K_{1\text{min}}$ | $K_{2\text{min}}$ | Straightness error |
|--------------|--------------|-------------------------|------------------------|-------------------|-------------------|--------------------|
| (0.6485,11)  | (0.276,249)  | (0.7015,486.2)          | (-0.208,37.103)        | 67.497            | 238.926           | 4.4761             |

### Table 4. 65 Roller Inspection (Replenishment) Table

| Roller number | Center of mind | length | Diameter | Taper | Concentricity |
|---------------|----------------|--------|----------|-------|---------------|
| 6501          | (-0.0484,-0.0124) | 1200.383 | 65.05341 | 1:1452 | 0.0772 |
| 6502          | (-0.0468,0,0295)  | 1200.327 | 64.77933 | 1:1414 | 0.10638 |
| 6503          | (0.0471,0,0687)   | 1200.433 | 65.14717 | 1:1393 | 0.12557 |

Analytical measurement methods show that the factors affecting measurement uncertainty mainly include the uncertainty $U_1$, $U_2$ caused by repeated measurements of length and diameter, and the uncertainty $U_q$, $U_h$ caused by the indication error of the grating scale and laser sensor. $U_1$, $U_2$ adopts the Class A assessment method, $U_q$, $U_h$ uses the Class B assessment method, and the uncertainty $U_c$ is calculated after calculation [12]. As shown in Table 5.
Figure 4. 6502 post-compensation radius distribution

Table 5. Uncertainty Evaluation Calculation Table

|     |        |        |        |        |        |
|-----|--------|--------|--------|--------|--------|
| U₁  | U₂     | Uₚ     | U₇     | U₈     |
| 7.6273·10⁻⁸ | 0.1561 | 2.212·10⁻¹⁰ | 1.8·10⁻⁴ | 0.1561 |

The final roll inspection data is as follows:

Table 6. 65 Roller Inspection Data Sheet

| Roller number | Center of mind | Length              | Diameter             | Taper       | Concentricity     |
|---------------|----------------|---------------------|----------------------|-------------|-------------------|
| 6501          | (-0.0484,-0.01247) | 1200.383±7.6273·10⁻⁸ mm | 65.05341±0.1561 mm | 1:1452     | 0.0772 mm         |
| 6502          | (-0.04682,0.029538) | 1200.327±7.6273·10⁻⁸ mm | 64.77933±0.1561 mm | 1:1414     | 0.10638 mm        |
| 6503          | (0.0471,0.068746) | 1200.433±7.6273·10⁻⁸ mm | 65.14717±0.1561 mm | 1:1393     | 0.12557 mm        |

5. Conclusion
The roller taper parameter test method can automatically calculate the roller radius, taper and coaxiality information only by the length of the cylinder and the distance from the sensor to the end face of the roller, without human intervention calculation. The method has error analysis at the same time, and the error is separated after each type of error, which improves the detection precision and is suitable for high-precision roller detection. And obviously superior to manual detection: not only improve the detection accuracy, detection efficiency, but also can detect the taper, coaxiality, which can not be obtained by manual measurement. It has good anti-interference ability during data acquisition, has good practicability and high cost performance, and is easy to use in production site testing. According to the error analysis of the sampling error analysis of the straightness error and the rotation error in the detection device, the compensated roller diameter error is significantly reduced, but there are still some uncertainty errors, which are compensated by relevant statistical data and uncertainty evaluation method. After that, the final result is closer to the theoretical value.

Acknowledgments
On the occasion of the completion of this paper, I would like to express my heartfelt gratitude and sincere respect to Teacher Yang Qihua (Corresponding Author). Mr. Yang’s perseverance in scientific research, profound knowledge, factual work attitude, generous and modest personalism, and selfless dedication have always inspired me to constantly learn knowledge and pursue the realm of life.
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