Research on Non-Contact Measurement Method of the Radial Circular Run-out Error of the Shaft Parts

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Abstract: At present, in view of a bridge shell axial parts artificially by dial indicator to measure the radial problem of low precision. This paper proposes to use a frequency domain three-point method of shaft parts’ non-contact laser measurement. It mainly includes the establishment of the design of the measurement model, the data collection, the data analysis and the data display system. The feasibility of the scheme is verified by a case. It’s a good technical support for the study of the radial circular run-out error of the shaft parts.

Introduction

At present, there are many researches on the radial circular run-out error of shaft section [1, 2, 3], Radial circle run-out error: Radial circle beating tolerance zone is in the vertical axis of any reference plane, the radius of the tolerance is “t”, and the center of the circle in the baseline axis between the two concentric circles, The tolerance band is limited to plane coordinates. It has many errors, including roundness error [4, 5], error of spindle rotation [6, 7] and tilt error of the installation axis. With the rapid development of precision and ultra-precision technology, roundness error separation is also becoming more and more important in the circular run-out error. In accordance with the structure and configuration of the sensor is divided into two point’s method, three-point method [6-8] and many methods for roundness detection. For thicker axes, the main measurement methods are micrometer [8], dial indicator, large vernier caliper and so on. The main method of enterprise is manual measurement [9, 10]. It leads to the low measurement precision and difficult to guarantee the measurement accuracy. For the current measurement of enterprise shaft parts. The authors propose a non-contact laser measurement method based on frequency domain three-point method, which includes the establishment of measurement model, data acquisition, data analysis and the design of the data display system. Through the case verification, which was proved the feasibility of the scheme.
Model Establishment
Measuring Principle

Figure 1. Three-point roundness measurement.

Three-point measurement principle shown in Fig.1. The point of O represents the origin of the coordinate system. The horizontal direction is the positive direction of the X axis. The vertical direction is the positive direction of the Y axis. And the Z axis is the axis of the axis. The three sensors are A, B and C and they incident light intersects a point and the intersection coincides with the axis. The point of intersection is O points. \( r(i) \) represents the surface. \( S_0(i), S_1(i) \) and \( S_2(i) \) represent the sensors’ outputs. \( \alpha \) and \( \beta \) represent the angle between the sensors. \( \delta_x(i) \) and \( \delta_y(i) \) represent the components of the X and Y spindle error.

\[
S_0(i) = r(i) + \delta_x(i) + \delta_y(i) 
\]

(1)

\[
S_1(i) = r(i + \alpha) + \delta_x(i)\cos \alpha + \delta_y(i)\sin \alpha 
\]

(2)

\[
S_2(i) = r(i + \beta) + \delta_x(i)\cos \beta + \delta_y(i)\sin \beta 
\]

(3)

Then, \( p_1 \) and \( p_2 \) are integers. \( p_1 = \alpha N / 2\pi, p_2 = \beta N / 2\pi \). For the above discretization, the matrix form:

\[
S_s = A_s E_s 
\]

(4)

\[
S_s = [S_0(i), S_1(i), S_2(i)]^T 
\]

(5)

\[
E_s = [v(i), v(i + p_1), v(i + p_2), \delta_x(i), \delta_y(i)]^T 
\]

(6)

\[
A_s = \begin{bmatrix}
1 & 0 & 0 & 1 & 0 \\
0 & 1 & 0 & \cos(2\pi p_1/N) & \sin(2\pi p_1/N) \\
0 & 0 & 1 & \cos(2\pi p_2/N) & \sin(2\pi p_2/N)
\end{bmatrix} 
\]

(7)

Assumptions:

\[
C = \left\{ 
\begin{array}{l}
  c_1 = -\sin \left[ \frac{2\pi(p_2 - p_1)}{N} \right] / \sin \left[ \frac{2\pi p_2}{N} \right] \\
  c_2 = \sin \left[ \frac{2\pi(p_2 - p_1)}{N} \right] / \sin \left[ \frac{2\pi(p_2 - p_1)}{N} \right]
\end{array} \right.
\]

(8)
C multiply equation (4) that the result was expanded and simplified as follows:

\[ Y_n(i) = r(i) + c_1(i + p_1) + c_2(i + p_2) \]  \hspace{2cm} (9)

Fourier transform can be used to solve the frequency domain expression of the roundness error of the measured parts.

\[ R(l) = \frac{Y_n(l)}{G(l)} \]  \hspace{2cm} (10)
\[ G(l) = C\Omega \]  \hspace{2cm} (11)
\[ \Omega = \left( e^{-j\frac{2\pi p_0}{N}}, e^{-j\frac{2\pi p_1}{N}}, e^{-j\frac{2\pi p_2}{N}} \right)^T \]  \hspace{2cm} (12)

formula: \( G(l) \)-weight function.
\( \Omega \) - Error separation phase shift rotation factor.
Equation (9) is the basic equation of three-point method roundness error separation. For any number of harmonics \( l \) if its weight function not equal to zero. The inverse Fourier transform is performed on (9) to find the roundness error.

Effect of Measurement Parameter Selection on Harmonic Suppression

The value of the separation weight \( G(l) \) is an important factor affecting the accuracy of error separation.

Bring (8) and (12) into (11). Assume \( P_0 = 0 \). then.

\[ G(l) = 1 - \frac{\sin(2\pi P_2/N)}{\sin[2\pi(P_2-P_3)/N]}e^{j2\pi lP_1/N} + \frac{\sin(2\pi P_1/N)}{\sin[2\pi(P_2-P_3)/N]}e^{j2\pi lP_2/N} \]  \hspace{2cm} (13)

It can be shown that when \( P_1, P_2 \) and \( N \) have a common factor of \( f \).

\[ G(l) = \begin{cases} 
  \neq 0 & l \neq \left( k\frac{N}{f} \right) \pm 1 & 0 \leq l \leq N/2 \\
  = 0 & l = \left( k\frac{N}{f} \right) \pm 1 & 0 \leq l \leq N/2 
\end{cases} \]  \hspace{2cm} (14)

Formula: \( k \) — arbitrary integer.

As a result, it is possible to make all \( G(l) \) not equal to zero other than \( l = 1 \) as long as the values of \( P_1 \) and \( P_2 \), and \( N \) are selected so that they have the greatest common factor \( f = 1 \) and can avoid harmonic suppression. However, regardless of the value of \( P_1 \) and \( P_2 \), \( G(l) \) equal to zero that always was held. The first order harmonic component suppression has a serious impact on the measurement results for high-precision measurement. Usually, workpieces eccentricity is the primary harmonic component of the measured profile. The first-order harmonic suppression characteristic eliminates the effect of eccentricity that making the roundness of the shape error assessment simpler.

The Evolution of Three-point Error Separation

Two-Point Error Separation Technique

From the measurement of three-point, if \( \alpha = \pi/2, \beta = \pi - \Delta\theta \) and \( N \) is large, so,

\[ c_1 = \frac{\sin\beta}{\sin(\alpha - \beta)} = \frac{\sin(\pi - \Delta\theta)}{\sin\left(\frac{\pi}{2} - \pi + \Delta\theta\right)} = \frac{\sin(\Delta\theta)}{\cos(\Delta\theta)} \approx 0 \]  \hspace{2cm} (15)
\[ c_2 = -\frac{\sin \alpha}{\sin(\alpha - \beta)} = \frac{\sin\left(\frac{\pi}{2}\right)}{\sin\left(\frac{\pi}{2} - \pi + \Delta \theta\right)} \approx 1 \quad (16) \]

This means that the sensor 2 output signal occupies a small weight in the weighted sum of the signals and can be ignored. Then, the three-point method is transformed into a two-point method.

**Four-Point Error Separation Technique**

On the basis of the three-point method with a sensor, it becomes a four-point method. Four-point methods of the thread equations are infinitely more sister.

\[
\begin{align*}
1 + c_1 \cos \alpha + c_2 \cos \beta + c_3 \cos \gamma &= 0 \\
c_1 \sin \alpha + c_2 \sin \beta + c_3 \sin \gamma &= 0
\end{align*}
\quad (17)
\]

That is, the sensor weight coefficient has a variety of options. This is equivalent to the re-design of measurement agencies to add the additional variables for the weight coefficient and the weight function. Through the weight coefficient of different values, you can get the desired accuracy of measurement.

**Evaluation of Three-Point Measurement**

When the roundness error of the cross section is measured by three-point method, the roundness error of the cross section and the rotation error of the spindle can be separated within one week.

However, the three-point measurement method has defective as follows:

1. In the actual measurement process, it is difficult to ensure the intersection of the incident light three sensors, the workpiece center of the cross-section and the rotation axis of the center of rotation at one point. In the separation algorithm, it’s has a first-order harmonic suppression and it cannot be separated out of the eccentric motion caused by installation trajectory.

2. In the process of solving, the algorithm is complex, and there are zero points in the algorithm. These problems need to be avoided, which leads to the complexity of the programming algorithm and the difficulty of programming.

3. No matter how the sensor layout, the harmonic suppression will occur in the three-point sensor measurement. The first harmonic cannot be separated and can get the purely rotary error motion.

**Data Acquisition System Design**

**Data Collection Design**

Figure 2 shows the structure of the measuring system of the shaft parts. According to the design requirements, the main design includes three parts: data acquisition layer module, data transmission layer module and host computer software layer module.

![Figure 2. The structure of the measuring system of the shaft parts.](image)
Data Acquisition Layer

The data acquisition layer consists of three laser probes and a controller, which used to acquire the surface information of the shafts. The Keyence sensor probe model is IL-065 and the controller model is IL-1050. The sensor accuracy is 2µm and the measuring range of the sensor is 50-105 mm.

The work piece is rotated under the rotation of the spindle and the rotation position angle of the workpiece is obtained by the encoder on the rotary spindle. After people setting the rotation zero point of the workpiece and the device is started. When the device reaches the designated position, the sensor collects the surface information of the rotary axis in real time. The system is developed by the VS2010. The use of timer function is “OnTimer ()” and the timer function was set up to carry out every 0.25ms once. Each section of the workpiece is equally divided by 128 points. The motor pulse frequency is 6400.

Data Transmission Layer

The data transmission layer mainly includes solid high GTS-400 movement card and RS-232 communication module. When the axis part rotates, the movement control card receives the information of encoder and sends high and low level signal to touch off the sensors to gather information. Three sensors’ data were collected by the RS-232 communication module. And then, they sent the information to the host computer. Laser displacement sensors can collect data at multiple frequencies.

The system uses RS-232 serial communication and laser displacement sensors collect information through the high and low level. The solid high-motion control card provides many functions and it’s very convenient and practical for users. The measurement uses “GT_SetDo ()” to set I/O output status. Sensor data acquisition is digital and the format is different from what we want. So, we need to deal with them by software.

Host Computer Software Layer

The host computer software layer mainly includes sensor data display module and data processing module. The sensor data display module includes non-automatic and automatic data acquisition. Non-automatic data display by the mouse trigger button, the data is displayed once for each trigger. Non-automatic data acquisition is shown in Figure 5 below. When the button is clicked, the interface will enter into Fig. 6 and the data will be collected automatically. When the mouse is clicked about the start button, the motor drives workpiece to rotate. The laser displacement sensor collects the data of axis in real time. The sensors stop after one week of data acquisition. The measuring device returns to the set position and waits for the next measurement.

![Figure 3. Non-automatic collected data display.](image1)

![Figure 4. Automatically collected data display.](image2)

Data processing module mainly developed based on VS2010 software and then call MATLAB for data processing. For the data processing, MATLAB as commonly used numerical calculation
software, which has the advantages of simple and fast matrix solution. However, the program of VS2010 is more complicated than MATLAB. It’s very simple that VS2010 call MATLAB dynamic link library for data processing. In the measurement, the data measured by the three sensors are stored respectively in the three variables Sdata1 [i], Sdata2 [i] and Sdata3 [i]. Then, VS2010 use the CStdioFile class to export the txt text. People use the algorithm to process the data to get the desired results. Finally, VS2010 call MATLAB dynamic link library approach to get the roundness error, rotation error and the corresponding image of error contour.

Case Study

In this case, a shaft with a diameter of 100 mm was tested. Three sets of sensors simultaneously collect data. Each group of sensors collects 128 points and the results are as follows: unit: (µm)

The circularity error (i) is 0.6264, the rotation error δ(x) is 6.3281 and δ(y) is 9.3238. Roundness error and rotation error contours are shown in Figures 8, 9 and 10. From the data obtained by the above processing, it can be seen that the rotation error is large. Through the above data, rotary error relative roundness error is much larger, mainly due to the workpiece installation tilt and spindle rotation deviation. Compensating the rotational error and improving the installation accuracy are the effective methods to improve the machining accuracy.

![Figure 5. Roundness error r (i) µm contour image. Figure 6. Rotational error δx(i)µm contour image.](image1)

![Figure 7. Rotational error δ y (i) µm contour image.](image2)
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Summary

This paper proposes to use a frequency domain three-point method of shaft parts’ non-contact laser measurement. It mainly includes the establishment of measurement model, data collection and data analysis. Finally, the components of radial circle runout of shaft parts are verified by case analysis. The roundness error and rotation error are separated successfully. It’s not only validate the feasibility of the scheme, but also improve the measurement precision.

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