Study on Flatness Error Measurement System of Large Plane based on Laser Dots

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Abstract. In order to meet the needs of large plane’s flatness error measurement and aim at the time-consuming, laborious, expensive and inefficient problems, a flatness error measurement system of large plane based on laser dots was designed. The measurement system scanned the plane by the distance sensor which was driven by a double degree-of-freedom rotating platform. The Euler angles of distance sensor and the displacement data between the distance sensor and the measured plane were collected by the data acquisition card. Then the measurement system obtained the spatial coordinate values of laser dots through data processing. Eventually, the actual surface was reconstructed and the flatness error was calculated. The measurement results showed that the system could accurately reflect the actual surface and had great significance in promoting the industrial application of large plane’s flatness error detecting device.

1. Introduction

With the development of the manufacturing industry, the customers’ requirements on the quality of product are more and more high. The flatness error is the shape error of the product surface, which directly affects the quality of product\textsuperscript{[1]}. At present, the flatness error measurement technology of minor plane is relatively mature, but there are still some problems in the measurement of large plane’s flatness error. Therefore, finding a reliable large plane’s flatness error measurement method is of great significance for the development of large plane’s flatness error measurement.

Flatness measurement methods can be roughly divided into contact measurement and non-contact measurement. Contact measurement methods mainly include manual measurement and three-coordinate measurement, but they have some shortcomings such as slow speed and easily scratching the measured plane\textsuperscript{[2]}. Non-contact measurement methods mainly include image analysis method and laser measurement method. The image analysis method is mainly based on parallel detection technology of machine vision, and the laser measurement method is mainly based on fixed point measurement method of distance sensor. Non-contact measurement methods have the advantages of real time and fast speed\textsuperscript{[3,4]}. The laser ranging technique is widely used for flatness measurement at present, which manifests the merit of reliable data, good straightness and strong anti-jamming capability.

To overcome the problem mentioned above, a large plane’s flatness error measurement system based on laser dots was designed in this paper. The results demonstrated that the measurement system had the advantages of large measurement range, high cost performance and good portability, which could accomplish flatness error measurement of large plane.
2. General design of the system

2.1. Design of general structure

The general structure of the measurement system is shown in figure 1, which is divided into three modules. The three modules are measurement mechanism, framework and control cabinet.

![Figure 1. General structure.](image1)
![Figure 2. Measurement mechanism.](image2)

The framework mainly consists of a beam and brackets. The distance between the measurement mechanism and the measured plane can reach 3600mm by extending brackets. By adjusting the height of brackets and inputting length and width of the measured plane to the host, the planes of different sizes can be detected. The maximum measurement range of the measurement system is 6000mm in length and 3000mm in width.

The measurement mechanism is shown in figure 2, which mainly consists of two servo motors, two high-precision rotating platforms and a distance sensor. A high-precision rotating platform and a servo motor constitute the pitch motion mechanism of the measurement mechanism and the rotation axis of platform is the \( y_0 \)-axis. A distance sensor, a high-precision rotating platform and a servo motor constitute the yaw motion mechanism of the measurement mechanism and the rotation axis of platform is the \( x_1 \)-axis. By pitching motion and yawing motion, the distance sensor scans the measured plane back and forth with S-shaped trajectory. \( O_{\Delta X Y Z 0} \) is the fixed coordinate system, \( O_{X Y Z 1} \) is the pitch coordinate system, which rotates around the \( y_0 \)-axis of the fixed coordinate system.

The control cabinet is mainly equipped with host, a touch screen and power. The self-locking universal wheels are mounted on the bottom for easy movement.

2.2. System software design

In order to realize the visual display of information for the measured plane, the host software, the programs of data processing and the programs of surface fitting were designed. Frame of software design is shown in figure 3. The host software adopted VC++ to realize multiple display screens, data communication and the motion control\[^5\]. The flatness error evaluation and the reconstructed surface were implemented by VC++ and mixed programming with external 3D software \[^6, 7\].
3. System measurement principle and model

3.1. Work principle of measurement system

The working principle of measurement system is shown in figure 4.

In figure 4, \( O_{0x0y0z0} \) is the fixed coordinate system. \( O_{1x1y1z1} \) is the pitch coordinate system, which rotates around the \( y_0 \)-axis of the fixed coordinate system. \( O_{2x2y2z2} \) is the yaw coordinate system, which rotates around the \( x_1 \)-axis of the pitch coordinate system. The pitch angle is called \( \alpha \), which contains the pitch angle error. The angle means the distance sensor rotates around the \( y_0 \)-axis. The yaw angle is called \( \beta \), which contains the yaw angle error. The angle means the distance sensor rotates around the \( x_1 \)-axis.

At first, the distance sensor rotated clockwise around the \( y_0 \)-axis by some angles namely \( \alpha \) and scanned from the end of the measured plane in the positive direction of the \( y_0 \)-axis. When it reached the other end, it rotated clockwise around the \( y_0 \)-axis by some angles and scanned along the \( y_0 \)-axis conversely. Measurement mechanism repeated the above scanning action to complete the S-shaped trajectory, and the scanning process was terminated after the set scanning times were reached. In the process, the data were collected by the host, which included the pitch angle namely \( \alpha \), the distance namely \( L \) and the yaw angle namely \( \beta \). The above angles were obtained by feedback of servo motors. The three-dimensional coordinates of laser dots were obtained from the data collected by D-H transformation. Taken any laser dot namely \( P(\alpha, \beta, L) \) on the measured plane as an example, the three-dimensional coordinates relative to the fixed coordinate system was expressed by \( (x, y, z) \).

\[
P(\alpha, \beta, L) \rightarrow P(x, y, z)
\]  

(1)
If the mapping relation (1) was realized, the following transformation was required.

\[ \mathbf{P}_1 = \mathbf{R}_1 \times \mathbf{T}_2 \times \mathbf{R}_2 \times \mathbf{P} \]

The formula (2) could be expanded.

\[
\begin{bmatrix}
\alpha_i \\
\beta_i \\
\gamma_i \\
1
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 \\
-\alpha & 0 & \alpha & 0 \\
0 & 0 & 1 & 0 \\
1 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\alpha & 0 & \alpha & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
0 \\
1
\end{bmatrix}
\]

The three-dimensional coordinates of each laser dot on the measured plane were calculated by equation (3). In addition, flatness error evaluation of the measured plane was realized by the least squares method.

3.2. Model of flatness error evaluation

The departure from flatness is the variation of the actual plane to its ideal plane, and the position of the ideal plane should meet the minimum condition\(^{(4)}\). The departure from flatness is expressed by the width of the minimum zone of flatness namely \(f\) in figure 5.

![Figure 5. Departure from flatness.](image)

The evaluation methods mainly include the minimum zone method, the three-point method, the diagonal method and the least squares method\(^{(1)}\). The least squares method can more accurately reflect the total error trend of the measured plane. Therefore, the least squares method is used by the measurement system. Finding an ideal plane (least squares mean plane) minimizes the sum of the square of distance that means the measured points on the measured plane to the ideal plane. In addition, the ideal plane (least squares mean plane) is used as the reference plane. Two planes are made and parallel to the reference plane. The above two planes contain the actual plane, and the distance between the two parallel planes is the departure from flatness\(^{(9-12)}\).

Calculating the departure of each measurement point namely \((x_i, y_i, z_i)\) relative to the least squares mean plane, which expressed by \(D\). The maximum value was called \(D_{\max}\) and the minimum value was called \(D_{\min}\) in \(D\). The difference between them was the departure from flatness that expressed by the formula (4).

\[ f = D_{\max} - D_{\min} \]

4. Calibration and analysis of measurement results

4.1. Calibration of the distance sensor

4.1.1. Calibration of distance sensor accuracy. First of all, the distance sensor was installed, which put right against the reflector with a distance. Then the displacement data between the distance sensor and the reflector were collected and recorded. Finally, the accuracy and repeatability of the distance sensor were analyzed by comparing the actual value with the measurement value. Additionally, it was also necessary to tilt the distance sensor with respect to the reflector by the angles of 15°, 30°, 45°, 60° and 75°. When the distance sensor was tilted at an angle each time, the displacement data were collected and compared with the actual measured values. The signals were revised by the above calibration, so that the signals more accurately reflected the actual values.
4.1.2. **Calibration of the initial position of the distance sensor.** As shown in figure 6, when the two servo motors were in home (initial position), the laser beam of distance sensor should be vertically downward in the theoretical state. In addition, when the rotating platform that controlled the pitch motion rotated 90° clockwise around the \( y_0 \)-axis, the rotating platform that controlled the yaw motion rotated 180° clockwise around the \( x_1 \)-axis, the laser dots of the distance sensor fallen at the intersection of the crosshairs on the calibration board. Due to the installation error, the error of servo motors, rotary platform transmission error and so on, the laser dots of the distance sensor couldn’t fall at the intersection of the crosshairs on the calibration board. Under the circumstances, the two servo motors were manually adjusted by the calibration program so that the laser dots fallen at the intersection of the crosshairs on the calibration board. During the process, the calibration program automatically recorded the angles of the two servo motors. The error angles of each rotation direction could be obtained by calculation.

![Figure 6. Process of calculation.](image)

4.2. **Case study**

In order to check the correctness and accuracy of the measurement system, the planes with different deformation were measured by the measurement system.

(1) A flat plane was measured as well as the measurement results were compared with the actual plane. Measurement results of flat plane were shown in figure 7.

![Figure 7. Flat plane.](image)

A large number of points in figure 7 were points cloud, which were calculated from the collected data by D-H conversion. The measured plane was reconstructed and the departure from flatness was calculated by points cloud data. In figure 7, the reconstructed surface was extremely similar to the
actual plane and the departure from flatness was 3.42 mm. The measurement results were in agreement with the actual measurement. On the basis of the analysis above, it might be safely concluded that the measurement system was satisfactory.

(2) When the measured plane had obvious deformation, rubber pads with thickness of 50.5 mm were added to both ends of the plane. The measurement results were shown in figure 8.

![Deformed plane of actual](image1)

![Measurement results of deformed plane](image2)

Figure 8. A plane with obvious deformation.

It could be seen from figure 8 that the reconstructed surface was extremely similar to the actual plane. They were flat in the middle and warped on both sides. The departure from flatness was 51.02 mm, which was intensely close to the height of the rubber pads. From the cases above, we might come to the conclusion that the measurement system was precise and reliable.

5. Conclusion
(1) From the actual situation, the flatness error measurement system was designed, which was mainly for flatness error measurement of large plane. Its maximum measurement range was 6000mm in length and 3000mm in width.

(2) The measurement system was modular, portable as well as convenient to assemble and disassemble. The measurement system was not only easily to operate and man-machine coordination, but also could output the measurement results automatically and display the measurement results visually.

(3) Although the maximum measurement range of the measurement system could reach as described above, the optimum measurement range was 5000mm in length and 2000mm in width. In the optimal measurement range, the measurement accuracy was high. When it exceeded the measurement range, it could be measured but the accuracy fell.

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