Research on the Measurement of the Gravity Center for the Workpiece with Complex Curved Surface

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Abstract—Taking the 300 kg-class single blade of the controllable pitch propeller as the research object, based on the principle of three-point gravity measurement, a secondary weighing method is developed, which obtained the relative coordinate value of the gravity center by making a difference between the two weighing data. According to the concept that each axis is independent, an error model of spatial attitude is established. The attitude deviation is obtained by using sensor scanning, and the actual coordinate value of the blade gravity center is obtained by combining with the space attitude transformation matrix. The experimental results indicated that the secondary weighing method with the space attitude transformation matrix in this paper was useful and highly accurate. The method has certain guiding significance for the gravity center measurement for workpieces with large and complex curved surface.

1. INTRODUCTION
The single blade of the controllable pitch propeller is a rotary body workpiece with complex curved surface. Due to the influence of non-design factors such as manufacturing error and positioning deviation, the actual center of gravity position of the single blade after machining is deviated, resulting in the single blade unable to meet the requirements of ISO484 and GJB3546. Therefore, the single blade static balance correction of the controllable pitch propeller is inevitable [1]. Measuring the gravity center for the single blade is the basis and prerequisite for the static balance of the controllable pitch propeller. The characteristics make that the error cannot be determined and eliminated by theoretical design, and the gravity center must be measured by experiment [2-3].

At present, the measurement methods of gravity center of single blade adopted by controllable pitch propeller manufacturers mainly include fulcrum balance method, moment measurement method and three-point gravity center measurement. L.B. Chubb [4] designed a single blade gravity center measuring device based on fulcrum method. It has the simple structure, but high-level operator skills and poor measurement repeatability. B. Chen [5] proposed a measuring device based on the torque method, which was highly automated, easily operated, but the equipment versatile was poor. Y.D.
Liang et al. [6] developed a tilt measurement method and device, which realized the measurement of 300 kg-class single blade. However, in practical applications, the above methods still have problems such as difficulty in blade positioning, large measurement error and small measuring range of equipment, which need to be solved urgently [7-9].

Taking a 300 kg-class single blade of marine controllable pitch propeller as the research object, the theory and practical methods of the gravity center measurement are studied. The structure and algorithm of the secondary weighing method based on the three-point gravity center method are designed, combing spatial attitude measurement and deviation compensation, realizing the fast and accurate measurement of the gravity center of the single blade, which can provide a reliable basis for the static balance and repair of the controllable pitch propeller.

2. MEASUREMENT PRINCIPLE

2.1 Secondary Weighing Method

The main purpose of the gravity center measurement of the single blade is to obtain the deviation between the Y-direction and Z-direction coordinates values of the gravity center of a single blade in a set of blades and the average value of the whole set of blades [5-6]. The single blade surface is a complex curved surface. The single blade gravity center measuring device currently used by manufacturers makes the sensor contact with the single blade curved surface directly. There is a side component force, which leads to the deviation of sensor data and affects the measurement accuracy.

Based on the principle of three-point gravity center measurement, this paper developed a double-layer separated weighing structure, as shown in Fig. 1. The measuring platform is mainly composed of paddle stanchions, V-shaped clamp fixture, force sensors, work board and guide posts. With this structure, a novel secondary weighing method is proposed: the single blade is placed on the work board,
and the work board is dropped for weighing. The force values $P_1'$, $P_2'$, $P_3'$ of the work board and the single blade are obtained through three force sensors. After lifting the single blade by the crane, the force values $P_1''$, $P_2''$, $P_3''$ of the work board can be obtained by the second weighing. According to the calculation formula of the secondary weighing (1-3), the relative coordinate value of the gravity center of the blade can be obtained by making the difference.

$P = \left( P_1' - P_1'' \right) + \left( P_2' - P_2'' \right) + \left( P_3' - P_3'' \right)$

$Y = \frac{\left( P_1' - P_1'' \right) \times Y_1 + \left( P_2' - P_2'' \right) \times Y_2 + \left( P_3' - P_3'' \right) \times Y_3}{P}$

$Z = \frac{\left( P_1' - P_1'' \right) \times Z_1 + \left( P_2' - P_2'' \right) \times Z_2 + \left( P_3' - P_3'' \right) \times Z_3}{P}$

Compared with the traditional device, the double-layer measuring platform structure combined with the secondary weighing method converts the lateral force into the internal force of the work board, eliminating the measurement error caused by the lateral force. The work board is limited by the guide posts, which ensures the repeated consistency of the contact point of the force sensor and solves the problems of fulcrum slip and unclear positioning.

2.2 Space Attitude Error Compensation

![Figure 3. Two-dimensional orthogonal diagram of blade attitude deviation](image)

Due to the large mass and complex surface of the single blade, there are some problems such as uncertain support and large space attitude deviation. As shown in Fig. 2, a Cartesian coordinate system is established for the work board and the blade respectively: the work board coordinate system O-XYZ is located on the work board and is fixed relatively to the ground; the blade coordinate system O'-X'Y'Z' is located on the blade positioning flange and rotates with the flange. The calculated gravity center position of the blade is relative to the platform coordinate system O-XYZ. Because of the incomplete overlap between the work board coordinate system and the blade coordinate system, the calculated gravity center position ($y', z'$) is not the actual gravity center position ($y'', z''$). Using the V-shaped clamp fixture and the double paddle stanchions fixed blade, its deviation of $\Delta x$, $\Delta z$ can be ignored, main profile deviation from the deflection Angle $\theta$, $\gamma$, $\Omega$ and displacement $\Delta y$, respectively to the plane of the two-dimensional orthogonal model, as shown in Fig. 3.
In this paper, an online measurement method of blade spatial attitude is presented, which can realize the accurate measurement of blade spatial attitude. Combined with the spatial coordinate conversion matrix, the actual gravity center coordinate value of the blade can be quickly and accurately converted from the relative coordinate value. According to the relationship between the two coordinate systems, the coordinate relationship between the relative gravity center position of the blade \((y', z')\) and the actual gravity center position of the blade \((y, z)\) is:

\[
(x', y', z', 1) = (x, y, z, 1) \cdot R_i
\]

When \(x\) is equal to 0, the transformation of \(x'\) is meaningless,

\[
R_i = \begin{bmatrix}
\cos \Omega \cos \theta & \cos \Omega \sin \theta & -\sin \Omega & 0 \\
\sin \gamma \sin \Omega \cos \theta - \cos \Omega \sin \theta & \sin \gamma \cos \Omega \sin \theta + \cos \gamma \cos \theta & \sin \gamma \cos \Omega & 0 \\
\cos \gamma \sin \Omega \cos \theta + \sin \gamma \sin \theta & \sin \theta \cos \gamma \sin \Omega - \sin \gamma \cos \theta & \cos \gamma \cos \Omega & 0 \\
\Delta x & \Delta y & \Delta z & 1
\end{bmatrix}
\]

Due to the bias of \(\Delta x, \Delta z\) are ignored, the matrix \(R_i\) can be simplified as \(R_2\):

\[
R_2 = \begin{bmatrix}
\cos \Omega \cos \theta & \cos \Omega \sin \theta & -\sin \Omega & 0 \\
\sin \gamma \sin \Omega \cos \theta - \cos \Omega \sin \theta & \sin \gamma \cos \Omega \sin \theta + \cos \gamma \cos \theta & \sin \gamma \cos \Omega & 0 \\
\cos \gamma \sin \Omega \cos \theta + \sin \gamma \sin \theta & \sin \theta \cos \gamma \sin \Omega - \sin \gamma \cos \theta & \cos \gamma \cos \Omega & 0 \\
0 & \Delta y & 0 & 1
\end{bmatrix}
\]

Then, (4) can be translated into:

\[
(x', y', z', 1) = (x, y, z, 1) \cdot R_2
\]

By scanning the blade flange disc surface with laser displacement sensor, 24 points of the disc surface can be obtained, and deflection angle \(\theta, \gamma, \Omega\) and displacement \(\Delta y\) can be obtained by calculation. The scanning point distribution is shown in Fig. 4.

![Figure 4. Distribution of scanning points on the surface of blade flange](image)

The acquisition process of deflection angle \(\theta, \gamma\) is similar. Taking deflection angle \(\theta\) as an example, the point coordinates \(X_{11}(x_{11}, y_{11}, z_{11})\), \(X_{12}(x_{12}, y_{12}, z_{12})\) are obtained by scanning. The computational formula is as follows:

\[
\theta_i = \arctan \frac{\Delta y_i}{\Delta x_i} = \arctan \frac{y_{12} - y_{11}}{x_{12} - x_{11}}
\]

Select \(X_{13}\) and \(X_{14}\), \(X_{15}\) and \(X_{16}\) in turn, calculate and obtain three groups of deflection angle \(\theta\) values, then take the average, and calculate and obtain deflection angle \(\gamma\) by scanning acquisition point \(X_{21} - X_{36}\).
Calculate the displacement $\Delta y$ by the above access point $X_{1i} \sim X_{16}$, $X_{2i} \sim X_{26}$, its formula is as follows:

$$\Delta y = \frac{\sum_{i=1}^{6} [(y_{1i} - y_e) + (y_{2i} - y_e)]}{212}$$  \hspace{1cm} (9)

$y_e$ is the distance between the blade flange disk surface in the ideal attitude and the origin of the work board coordinate system O-XYZ, and it is a fixed value. Deflection angle $\Omega$ is calculated depending on planar circle $C(x_e, y_e, z_e)$ and positioning-hole circle $E(x_e, y_e, z_e)$, its formula is:

$$\Omega = \arctan \left( \frac{x_e - x_c}{z_e - z_c} \right)$$  \hspace{1cm} (10)

The fitting process of center of locating hole and plane center are basically the same. Taking the fitting process of plane center $C(x_e, y_e, z_e)$ as an example, the points $X_{31} \sim X_{36}$ are obtained by scanning and the fitting equation is:

$$\begin{cases}
x_c = u_c + \overline{x} \\
y_c = \overline{y} \\
z_c = w_c + \overline{z}
\end{cases}$$ \hspace{1cm} (11)

$$\begin{cases}
u_c = \frac{S_{uu} - S_{uw} S_{uw} - S_{uw} S_{wu} + S_{wu} S_{wu}}{2(S_{uu} - S_{uw} S_{wu})} \\
w_c = \frac{S_{uw} - S_{wu} S_{wu} - S_{wu} S_{uw} + S_{uw} S_{uw}}{2(S_{uu} - S_{uw} S_{wu})}
\end{cases}$$ \hspace{1cm} (12)

$$\begin{cases}
\overline{x} = \frac{\sum x_{3i}}{N} \\
\overline{y} = \frac{\sum y_{3i}}{N} \\
\overline{z} = \frac{\sum z_{3i}}{N}
\end{cases}$$ \hspace{1cm} (13)

$$\begin{cases}
S_{uu} = \sum (x_{3i} - \overline{x})^3 \\
S_{uv} = \sum (z_{3i} - \overline{z})^3 \\
S_{uw} = \sum (x_{3i} - \overline{x})^2 \\
S_{vw} = \sum (z_{3i} - \overline{z})^2 \\
S_{uw} = \sum (x_{3i} - \overline{x})(z_{3i} - \overline{z}) \\
S_{uv} = \sum (x_{3i} - \overline{x})(z_{3i} - \overline{z})^2
\end{cases}$$ \hspace{1cm} (14)

The position coordinates values of the gravity center in the blade coordinate system can be calculated by substituting the 4 deviation values obtained in the final calculation into (6) and (7).
3. EXPERIMENT AND RESULT ANALYSIS

3.1 Description of the Experimental Equipment

According to the proposed gravity center measurement method, the corresponding experimental equipment was designed and developed, as shown in Fig. 5. During the measurement of gravity center, the blade is fixed on the work board by V-shaped clamps fixture and paddle stanchions. The measurement range of the equipment is 100-400 kg, and the work board is supported by 86 series stepping motors for lifting. The flange scanning sensor is a Panasonic laser sensor with a range of 200 mm and an error range of ±0.01 mm. The scanning point coordinates values are obtained by reading and converting the magnetic grid ruler reading head. Based on VB.net language, the human-machine interface of the equipment control system was developed in Visual Studio 2015. The lower computer program was written using ISP soft software provided with Delta PLC. The host computer includes functional interfaces such as load cell calibration and data acquisition, laser displacement sensor data acquisition and blade attitude adjustment.

![Figure 5. Experimental equipment diagram of the gravity center measurement](image)

3.2 Experiment and Data Processing

Using the developed measuring equipment to conduct the blade gravity center measurement test, the test object is a nickel aluminum bronze with the diameter of 1.42 m and single blade weighted 316.97 kg. Its position coordinate value in Y direction is 733.91 mm, and the value in Z direction is 118.34 mm. The maximum allowable deviation in Y direction is 0.15 mm, and the maximum allowable deviation in Z direction is 0.4 mm.

The following steps are required for each set of experiments: (1) According to the quality, size and shape of the blade, the position of the paddle stanchions is roughly adjusted. Lift the blade, then initialize the device, reset the sensor, and next measure the load on the lowering work board with the blade. After completion, raise the work board and repeat this step to measure three sets of data; (2) lift the blade to separate it from the work board and then lower the working plate again for no-load measurement. After completion, raise the work board and repeat this step to measure the three sets of data. After the single set of experimental data is recorded, hang the blade, adjust its attitude, and enter the next set of experimental data for measurement.

Table 1 shows the experimental data obtained after three sets of blade center of gravity measurements. The unit of the measured blade mass $P$ is: kg; the unit of the coordinate values of the blade center of gravity $(y, z)$ before the coordinate conversion and the coordinate values $(y', z')$ after the coordinate conversion is: mm.

| Experiment Set | $y$ (mm) | $z$ (mm) |
|---------------|---------|---------|
| Set 1         | 733.91  | 118.34  |
| Set 2         | 733.92  | 118.35  |
| Set 3         | 733.93  | 118.36  |
TABLE I. EXPERIMENTAL MEASUREMENT RESULTS

| Group number | Serial number | \( P \)    | \( y \)   | \( z \)   | \( y' \) | \( z' \) |
|-------------|---------------|--------|--------|--------|--------|--------|
| I           | 1             | 316.94 | 729.37 | 119.80 | 733.91 | 118.25 |
|             | 2             | 317.04 | 729.48 | 119.77 | 733.85 | 118.33 |
|             | 3             | 316.97 | 729.45 | 119.75 | 733.82 | 118.39 |
| II          | 4             | 317.04 | 734.21 | 116.48 | 733.90 | 118.33 |
|             | 5             | 316.93 | 734.28 | 116.25 | 734.06 | 118.34 |
|             | 6             | 317.00 | 734.35 | 116.20 | 734.06 | 118.41 |
| III         | 7             | 316.95 | 730.45 | 121.68 | 733.92 | 118.13 |
|             | 8             | 316.98 | 730.62 | 121.99 | 733.93 | 118.10 |
|             | 9             | 317.00 | 730.42 | 121.88 | 733.92 | 118.08 |
| Average value |           | 316.98 | 731.41 | 119.31 | 733.93 | 118.23 |

Using the position coordinate values \((y, z)\) of the blade gravity center before the coordinate conversion in the table and the coordinate values \((y', z')\) after the coordinate conversion, a comparison curve of the Y and Z position coordinate deviations of the blade gravity center before and after the coordinate conversion is drawn. Selecting the blade quality \(P\) and coordinates values \((y', z')\), a curve based on the obtained deviation value by making a difference with their average value is drawn, as shown in Fig. 6.

It can be drawn from Fig. 6(a) that when the measurement is repeated in the group, the deviation range of the Y-coordinate value within the group is less than \(\pm 0.07\) mm, and the deviation range of the Z-coordinate value within the group is less than \(\pm 0.11\) mm, indicating that this double-layer weighing experiment method has good repeatability and measurement accuracy.

As can be seen from Fig. 6(a), (b), when the data measured by the work board has not been transformed by spatial coordinates, the Y-coordinate deviation range is about \(\pm 3.30\) mm, and the Z-coordinate deviation range is about \(\pm 3.11\) mm. The coordinate measurement results of the gravity center position have a significant influence. After the spatial coordinate conversion, the Y-coordinate deviation range is about \(\pm 0.13\) mm, and the Z-coordinate deviation range is less than \(\pm 0.21\) mm. At the same time, the range of blade quality deviation is less than \(\pm 0.1\) kg. The results show that the blade attitude error compensation method has a great effect, basically eliminating the influence of the blade attitude on the measurement results.

Figure 6. Deviation analysis chart of the blade quality and the gravity position before and after coordinate conversion
4. CONCLUSION
Compared with the existing center of gravity measurement method, the single blade gravity center measurement method proposed in this paper is simple in principle, practical, and has a wide range of applications. It is also suitable for the gravity center measurement of non-rotating workpieces with large and complex curved surfaces. This method can accurately measure and obtain the actual coordinates values of the gravity center of the blade by online measurement and coordinate conversion of the blade spatial attitude, even when the blade is not completely leveled. The method reduces the installation and positioning requirements for blade and shortens the measurement and the debugging time. Through the double-layer measurement structure, the lateral force component problem existing in the direct measurement of curved workpieces is eliminated, and the measurement accuracy is improved. The experimental results show that the method can realize the accurate measurement of the gravity center of the single blade of the controllable pitch propeller, which provides a reliable data reference for the static balance and repair processing of the single blade.

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