Development of Static Balance Measurement and Correction Compound Platform for Single Blade of Controllable Pitch Propeller

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Abstract. Aiming at the static balance of the controllable pitch propeller (CPP), a high efficiency static balance method based on the double-layer structure of the measuring table and gantry robot is adopted to realize the integration of torque measurement and corrected polish for controllable pitch propeller blade. The control system was developed by Microsoft Visual Studio 2015, and a composite platform prototype was developed. Through this prototype, conduct an experiment on the complete process of torque measurement and corrected polish based on a 300kg class controllable pitch propeller blade. The results show that the composite platform can correct the static balance of blade with a correct, efficient and labor-saving operation, and can replace the traditional method on static balance of the blade.

1. Introduction

Controllable pitch propeller (CPP) consists of multiple blades and hubs. Thanks to its advantage on achieving rapid thrust, large-scale changes by rotation of the blades around its own axis to change their spacing distribution \[1, 2\], CPP gradually become the mainstream on market. As the key factor in the life and vibration of the ship, static unbalanced moment of the pitch is required to meet the requirements of ISO484 and GJB3546. Therefore, it is necessary to carry out static balance measurement on CPP. Meanwhile, in order to ensure the Interchangeability between the blades, a single blade must be subjected to a static balance measurement. The static balance of single blade is the basis of the static balance of whole CPP, and its test accuracy will directly affect the accuracy of the static balance measurement on CPP \[2, 3\].

At present, the commonly used method of measuring the static balance of the pitch is mainly: the fulcrum method, the torque method and the center of gravity method. Chubb L B \[4\] uses a fulcrum method to design a blade static balance measuring device, its structure is simple, but the measurement method depends on the technical level and experience of the operator, and has the disadvantages of low efficiency and high labor intensity. Chen Bin \[2\] using the torque method to design a blade static balance device. The device solves the problem of low degree of automation and complicated operation process, but there are problems that the equipment has poor versatility, high manufacturing precision and high cost. Yan Xincun \[5\] have developed a method for the measurement of torque, which is mainly used in the overall balance measurement of aircraft, the feasibility can be demonstrated. The method, as the main measurement method, is gradually replacing the fulcrum method and torque method based on its better equipment versatility and operability. At home and abroad, some of the equipment based on this method have been put into application testing, but their structure is relatively simple, and there are problems such as vulnerable sensors and complicated calculation need to be solved. As the measuring device and grinding device independent of each other, after the completion of the torque measurement,
operators need disassemble the blade across and then polished it. Due to the special working condition of the blade, it should only be removed part of the material to adjust its static balance. In practice, the selection of grinding volume is generally conservative. Therefore, it is necessary to disassembly positioning and measurement grinding repeatedly. So now process of static balance on CPP still exists many issues such as difficult to locate, repeatedly moving positioning, low grinding efficiency, manpower loss to be solved.

In this paper, a composite platform based on static balance measurement and correction is proposed, which uses the method of double weighing and the algorithm of attitude compensation in space to realize the accurate measurement on unbalanced torque of the blade. On the one hand, combined with the flexible grinding method of the robot, the platform is able to achieve efficient grinding; On the other hand, by the integrated design on measurement and correction structure, the platform can reduce the number of blade handling and the overall processing time.

2. Study on the process and principle of static balance for single blade

The process of static balance of CPP includes two parts: torque measurement and modified grinding. The phase of torque measurement is mainly to measure the deviation of the unbalanced torque \( M_z \) and \( M_y \) of a single blade in a set of blades. The phase of modified grinding is to correct compound platform for the single blade so that the unbalanced torques of the whole blades are in the same range. At present, the domestic and foreign shipyards generally use the device of center of gravity measuring and artificial correction for the static balance. The main problems are as follows: (1) the requirements of blade positioning are very high and the installation is difficult; (2) the position of weighing fulcrum is ambiguous and the repetition of precision is very low; (3) there is lateral force at the fulcrum, affecting the accuracy of measurement; (4) artificial correction led to high labor intensity.

![Figure 1. Schematic diagram of the measurement of space posture.](image)

(a) Paddle posture compensation  
(b) Actual focus

As shown in figure 1, for the problems about positioning and installation of blade, this composite platform uses the displacement sensor and magnetic railing ruler to scan and calculate the edge of blade. Specific steps are as follows:

1. Measure the coordinates of the different edges of the blade flange and the edge of the positioning hole, establish the coordinates of the flange surface, and calculate the center coordinate of the flange surface and the center coordinates of the positioning hole.
2. Perpendicular to flange plane and through the center of flange and positioning hole, create a plane in which the center of gravity of the blade located by deflecting a fixed angle.
3. Through the theoretical focus measured, create a line which perpendicular to the YZ surface, the intersection \( (p) \) of the line and the center of gravity of the blade, that is, the actual coordinates.

Through above methods, combined with software of the algorithm developed, you can directly calculate the space posture of blade with computer, to achieve compensation to the space posture of blade. In this way, the measurement error caused by installation and positioning can be eliminated, meanwhile the requirement and difficulty of blade placement are reduced.
In this paper, through the design of the double-layer platform structure (Figure 2). The lateral force is transformed into the internal force of the platform by the secondary weighing method, and the lateral component force is eliminated. And the introduction of the guide component of the weighing point to limit the point to ensure that the secondary weighing process in the support point positioning accuracy and repeatability. This solves the problem of the fissure slip and the ambiguity of the traditional measurement. At the same time, this paper designed a real-time compensation of the flexible grinding mechanism, the grinding machine at the bottom of the linear guide and double-layer measurement of the lower channel steel frame connected to achieve the measurement of grinding automation and integration, reducing the number of blade disassembly and labor Strength, shortening the processing cycle relative to the traditional single Blade static balance device greatly improved efficiency and accuracy.

3. Design of composite platform

In this paper, a composite platform for measuring and correcting static balance of CPP blade is shown in Figure 3. The device consists of a double-layer measuring platform, the platform for the measurement of the need to load the first no-load and a gantry manipulator. After no-load weighing and
load weighing, the quality \( (P) \) of the blade and unbalanced moment \( (M_x \) and \( M_y) \) can be got by the quadratic weighing algorithm, which means the static balancing of a CPP blade can get rid of iterative disassembly and assembly and just need plan the grinding process by host computer, then control the gantry manipulator to grind the blade to reach the standard.

3.1. The design of double-layer measuring platform
The double-layer measuring platform mainly includes work board, channel frames, guiding components, upper elevating mechanisms, lower elevating mechanism and V type clamp. When carrying out grinding, the lower elevating mechanism lifts and struts the work board to avoid excessive impact on the force sensors when hoisting and grinding, ensuring the precision and durability of the sensors.

The work board is the main bearing part of the double-layer measuring platform, whose strength and stiffness directly affect the measuring accuracy and stability of the composite platform. In this paper, ANSYS Workbench is used to optimize the configuration of stiffeners, and obtain the structure of work board which is shown in figure 3 (a). When the work board is at a total load of 317.4kg, its maximum strain is 0.024mm.

3.2. The design of laser displacement sensor and its rail frame
As is shown in figure 3 (b), laser displacement sensor and its rail frame are mainly composed of synchronous belt modules, motors, laser sensor, grating rulers. The laser sensor can move in two directions of space X and Y through two sets of synchronous belt modules and motors to measure and position the points on the flange of the blade.

Since the laser sensor positioning accuracy directly affects the accuracy of the attitude compensation and the precision of calculated moment, the requirement of accuracy can’t be met only by synchronous belt modules, consequently the magnetic grating rulers and position sensors are installed on the rail. The points can be measured when the sensors read magnetic grating rulers, whose positioning accuracy can reach 0.002mm, so as to ensure the accuracy of the final measurement of the blade’s gravity center is less than 0.01mm.

3.3. The design of grinding device
The grinding device is mainly composed of four parts, the portal frame, the manipulator, the air-spindle and the grinding head. The portal frame is arranged at the channel frames through the linear slide rails to move straight, providing more working space for the manipulator where different grinding requirements of variable blade specifications can be met.

An air-spindle is installed on the top of the manipulator, whose maximum buoyancy of the air bearing spindle is 60N, and the maximum float is 14mm. A displacement sensor is also installed on the spindle for data collection. When the grinding weight is out of the scope of upper and lower limit protection value, the PC controls manipulator to move in opposite directions to compensate the grinding weight, avoiding the grinding weight out of tolerance. At the same time, the spindle itself has a floating value, and the grinding weight is compensated passively under the sudden change of the blade surface, so as to ensure the smoothness of the blade after grinding.

4. Implementation of compound platform
The cost and versatility of the 300kg class are selected as the main processing objects, and the prototype of the composite platform is measured and modified according to figure 4 (a). The prototype can be used for the static range of 102.5kg-440kg single blade static balance measurement weighing and data recording, and can be based on the data after the completion of the paddle grinding path planning to achieve the gantry robot on the paddle automatic grinding.

At present, the commonly used control software development methods include Labview or configuration software and other graphical programming environment for the development and use of advanced programming language for the development of two [6]. In this paper, Visual Basic language is used to realize the development of man-machine interface of composite platform control system in Visual Studio 2015 software. The preparation of PLC program is carried out using ISPsoft.
As shown in figure 4 (b), the host computer includes load cell calibration and data acquisition, laser displacement sensor data acquisition and blade attitude adjustment and other functional interface. The left half of the interface is used to record the no-load, load measurement of the weighing data and the edge of the coordinates, after the measurement can be obtained directly through the interface paddle center of gravity coordinates and unbalance torque values; the right part of the path planning and Surface grinding function interface, grinding area and grinding mode can be selected to achieve a simple and efficient static balance measurement and correction.

![Composite platform load weighing and its software interface.](image)

(a) Prototype in kind  (b) software interface

**Figure 4.** Composite platform load weighing and its software interface.

### 5. Experiment
The static balance measurement and correction test were carried out by using the developed static balance measurement and correction composite platform. The test object was a nickel leaf and aluminum leaf with a diameter of 1.4m and a weight of about 320kg.

The specific test procedure is as follows:

1. According to the blade quality, size and shape, the upper lifting mechanism of the location of coarse adjustment, and lock the V-clamp body; then the platform initialization and reset the laser displacement sensor, down the work board no load measurement, after completion Rise platform;
2. Open the V-clamp body, the blade lifting and posture adjustment, and lock the V-clamp body; again down the work board for load measurement, after the completion of the platform, repeat the measurement of three sets of data;
3. Fine-tune the attitude of the blade, repeat (2) the process three times, and get three different paddle posture under the nine sets of data;
4. The host computer automatically calculates the parameters, according to the blade quality and unbalanced torque value grinding path planning, and automatic blade grinding.
5. Decrease the working plate, load the load again, if the blade quality and unbalanced torque values meet the requirements, then stop; otherwise, repeat (2), (4) until the process reaches the requirements.

Table 1 for the first load of the treated load was repeated for nine times the weight of the blade, the unbalanced torque before and after the compensation. Among them, the paddle quality \( P \) before space attitude compensation and the paddle quality \( P' \) after space attitude compensation are: kg; the unbalanced moment \( M_z \) and \( M_y \) before space attitude compensation, and the unbalanced moment \( M'_z \) and \( M'_y \) after space attitude compensation are: kg⋅mm.
Table 1. Test the measurement results.

| Group No | Serial number | P | $M_z$ | $M_y$ | $P'$ | $M'_z$ | $M'_y$ |
|----------|---------------|---|-------|-------|------|--------|--------|
| I        | 1             | 316.90 | 37973 | 231210 | 316.90 | 37481 | 232660 |
|          | 2             | 316.90 | 37981 | 231353 | 316.90 | 37524 | 232673 |
|          | 3             | 316.90 | 37896 | 231048 | 316.90 | 37528 | 232583 |
| II       | 4             | 317.00 | 36932 | 232538 | 317.00 | 37518 | 232744 |
|          | 5             | 316.90 | 36847 | 232733 | 316.90 | 37412 | 232664 |
|          | 6             | 316.90 | 36839 | 232869 | 316.90 | 37539 | 232663 |
| III      | 7             | 316.90 | 38568 | 231616 | 316.90 | 37444 | 232571 |
|          | 8             | 317.00 | 38734 | 231515 | 317.00 | 37438 | 232657 |
|          | 9             | 317.00 | 38649 | 231510 | 317.00 | 37443 | 232727 |
| Average Value | | 316.92 | 37824 | 231821 | 316.93 | 37481 | 232660 |

The unbalanced moments ($M_z$, $M_y$, $M'_z$, and $M'_y$) before and after the spatial posture compensation are selected, and the unbalanced moments and the data are respectively made with the mean value of the posture compensation, and the Y-direction and Z-direction unbalanced moments are plotted before and after the spatial posture compensation. Posture compensation after the paddle quality ($P'$) and spatial posture compensation ($M'_z$ and $M'_y$) after the unbalanced torque, the data, respectively, with its average value is poor, according to the deviation obtained by plotting the posture compensation after the paddle quality, unbalanced torque deviation curve, as shown in figure 5.

It can be seen from figure 5 (a) that the deviation of the Z-direction unbalance torque is less than ±1000kg · mm and the Y-direction unbalanced torque deviation is about ±900kg · mm when the measured data of the platform is not compensated by spatial attitude. Unbalanced torque measurement results have a great impact, after the spatial attitude compensation, Z-direction unbalanced torque deviation range is less than ±100kg · mm, Y-direction unbalanced torque deviation range of about ±70kg · mm system has a high measurement accuracy, The basic elimination of the attitude of the blade on the unbalanced torque measurement results.

![Graph](image)

(a) Y-direction and Z-direction unbalance torque deviation  (b) results after compensation

Figure 5. Deviation analysis chart of paddle quality and unbalance torque deviation.

It can be seen from figure 5 (a) and (b) that the range of the Z-direction unbalance torque deviation is less than ±100 kg·mm and the Y-direction unbalance torque deviation range is ±60 kg·mm, indicating that the system has a high measurement accuracy and good repeatability.

6. Summary

1) The design of a double-layer measuring table structure, through the laser displacement sensor and magnetic grid scale to achieve the blade space attitude measurement and compensation algorithm, combined with the secondary weighing algorithm can be measured method of the center of gravity pad
to solve the existing Method of the existence of the paddle positioning difficult, the measurement results are not accurate problems;

2) The grinding machine of the gantry robot is developed, and the grinding force is compensated by installing the displacement sensor on the grinding spindle, and the real-time passive compensation of the grinding amount is realized by combining the floating amount of the flexible air-floating spindle itself. Combined with the double-layer to achieve the integration of measurement and grinding, simplifying the static balance process of the blade to solve the problem of low efficiency, large human consumption;

3) The experimental application shows that the measurement principle, mechanical structure and control software of the composite platform are reasonable. The results show that the composite platform can correctly perform the static balance operation of the paddle blade, which can replace the traditional method the traditional static balance device, the composite platform in efficiency, cost, operational and so have a greater advantage.

7. References
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