Development and quality control method of variable torque propeller for wind tunnel power simulation

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Abstract. In order to study the comprehensive influence of propeller power and sea surface effect of a seaplane, a composite material variable torque propeller for wind tunnel power simulation was developed. In order to make the quality of wind tunnel test data meet the standard of engineering application and control the quality of propeller products, a quality control method was developed to control the quality of design, checking, manufacturing, verification and operation of the propeller in all stages. In this paper, the research and development process and quality control method of the propeller, tests and the detection results, as well as the application test are described in detail. The results show that the quality control method described in this paper can be used to design and manufacture the propeller products which match the technical indicators, and the power simulation system composed of the propeller can exert slipstream influence on a certain seaplane under various working conditions, so as to meet the requirements of the study on the comprehensive influence of propeller power and sea surface effect of the aircraft.

1. Introduction

Compared with conventional aircraft, seaplane has excellent lift-drag performance. In the lake and ocean environment, seaplane runs faster than all kinds of ships. It is safe, economical, high-speed, comfortable and free from air traffic control, so it has broad application prospects [1]. The sea is rarely calm and there are wind and waves in most of the time. Therefore, when flying close to the sea, the aerodynamics characteristics of the seaplane and the flow field structure around it are quite different from the horizontal water surface [2]. The motion parameters and derivatives of seaplane have significant nonlinear changes with flight altitude, which affect the flight stability [3]. The numerical study of Qin Xuguo [4] showed that the aerodynamic performance of the seaplane when cruising on the water surface would be greatly affected by the water surface wave, and the shape of the water surface wave would cause unsteady change of the aerodynamic force. At present, there are few researches in this field. From the published papers, researches focus on numerical simulation [4-7]. Wind tunnel test is a very economical and effective way to study the comprehensive influence of propeller power and sea surface effect of a seaplane (Figure 1). To meet the needs of wind tunnel test, the researchers developed four systems, namely power simulation system, wave simulation system, attitude simulation system and data acquisition system. The variable torque propeller discussed in this paper belongs to the power source subsystem of the power simulation system.

Power simulation variable torque propeller is characterized by small size and high speed. The difficulties in its development include the design and manufacture of cantilever and thin-wall structure,
The control of unbalance at high rotating speed, the realization of torque variation function and the repeatability of wind tunnel test data.

![Figure 1. Sketch map of the seaplane.](image)

In order to control the quality of propeller products, a quality control method was developed. To design, check, manufacture, verify and operation of the standard process and quality control points, and the key quality control points were tested and recorded. It should be noted that, the test method should be reviewed, so as to ensure the reliability of the test results, which is not discussed in detail in this paper.

Variable torque propeller is an essential equipment used in wind tunnel power simulation. DNW engineers represented by I. Philipsen established propeller power simulation systems in DNW-LST, DNW-HST and DNW-LLF wind tunnels respectively [8]. The ONERA engineer represented by J. Prieur established the propeller power simulation system in the Onera-SIMA wind tunnel and established the standard process for it [9]. S. Speck and Y. Nishizawa established propeller test devices that can measure thrust, torque, power, efficiency and other performance indicators in Germany and Japan respectively [10-11].

Engineers from China Aerodynamics Research and Development Center, represented by Li Zhengchu and Zhang Hui, established their propeller power simulation system and systematically studied the propeller slipstream test method [12-13]. Engineers of Aerodynamics Research Institute of AVIC, represented by Li Xingwei and Xu Chuanbao, established their propeller dynamics simulation system, and studied the coupling effect of propeller slip flow and deep stall with slipstream [14].

2. Design and manufacture

2.1. Design targets
The main targets of propeller design are to ensure the product's realizability and operation safety. Specifically, it includes ensuring the machinability of the cantilever and thin-walled propeller, checking its static strength and dynamic strength, ensuring that its dynamic frequency does not resonate with other test systems, and putting forward reasonable indicators requirements for manufacturing and testing in the final use state.

2.2. Technical indicators
After comprehensive consideration of each system, the technical indicators of propeller are presented in Table 1.
| Project                          | Indicators                  |
|---------------------------------|-----------------------------|
| Disc Diameter (mm)              | 310 ± 1                    |
| Number of Blades                | 6                           |
| The Highest Speed (rpm)         | ≥12000                      |
| Maximum Tension (N)             | ≥110                        |
| Dynamic Balancing Level         | G2.5                        |
| Blade Angle Adjustment Range    | ≥±20°                       |
| Leaf Blade Material             | Carbon Fiber                |
| Profile Accuracy Requirement (mm)| ≤±0.3                      |

2.3. The design and verification

Propeller hub adopts three-stage design which is shown in Figure 2, through interference fit, clamps the blades under each blade angle. To calibrate the angle of the rotating blade, a measuring tool as shown in Figure 3 is designed. Before being put into manufacturing, the finite element method is used to verify the design of propeller blade and hub. If the assessment cannot pass, the design needs to be optimized. Verification results are shown in Table 2.

![Figure 2. Sketch map of the propeller.](image)

![Figure 3. Blade angle measuring tool.](image)

| Project                  | Check Target               | Hub | Blade |
|--------------------------|----------------------------|-----|-------|
| Static Strength Check    | Safety Factor ≥3           | Pass| Pass  |
| Dynamic Strength Check   | Safety Factor ≥2.5         | Pass| Pass  |
| Harmonic Response Analysis| First Order Frequency (Hz) ≥50| Pass| Pass  |
2.4. The manufacturing process
In order to ensure the assembly quality of products and improve the tolerance level of the hub and blade fit, the hub manufacturing adopts a three-axis machining center to control the quality, and the blade manufacturing adopts a high-performance mold to control the quality.

Hub adopts high strength alloy steel manufacturing; blades are manufactured by T700 prepreg carbon fiber (Figure 4). The manufacturing and assembly results are shown in Table 3.

As can be seen from the table, the final manufacturing weight of the blade is controlled between 12.5g and 13.0g. In order to evenly distribute the weight of all propeller products, six steps distribution based on weight were adopted to distribute the propeller at the positions of 1# to 6# of each hub.

![Figure 4. Material object of the propeller.](image)

### Table 3. Propeller blade manufacturing and assembly results.

| Hub Serial Number | 1# | 2# | 3# | 4# |
|-------------------|----|----|----|----|
| Blade Serial Number | 1-1# | 1-2# | 1-3# | 1-4# | 1-5# | 1-6# |
| Measured Weight (g) | 12.54 | 12.58 | 12.59 | 12.63 | 12.67 | 12.90 |
| Hub Serial Number | 2# | 3# | 4# | 5# | 6# | 7# |
| Blade Serial Number | 2-1# | 2-2# | 2-3# | 2-4# | 2-5# | 2-6# |
| Measured Weight (g) | 12.50 | 12.57 | 12.66 | 12.77 | 12.84 | 12.98 |
| Hub Serial Number | 3# | 4# | 5# | 6# | 7# | 8# |
| Blade Serial Number | 3-1# | 3-2# | 3-3# | 3-4# | 3-5# | 3-6# |
| Measured Weight (g) | 12.52 | 12.58 | 12.70 | 12.78 | 12.86 | 12.99 |
| Hub Serial Number | 4# | 5# | 6# | 7# | 8# | 9# |
| Blade Serial Number | 4-1# | 4-2# | 4-3# | 4-4# | 4-5# | 4-6# |
| Measured Weight (g) | 12.54 | 12.61 | 12.70 | 12.79 | 12.90 | 13.00 |

3. Verification test

3.1. Profile accuracy test
The manufacturing precision of propeller blade will affect its aerodynamic performance. Therefore, after the manufacturing of propeller blade, the profile accuracy test is carried out first. Three coordinate measuring instrument is used to measure the position error of key points on five sections of the propeller. After the load simulation test, the blade profile is retested, and the profile deviation is required to be less than 0.3mm. The test results are shown in Table 4. It can be seen from the table that 7# blade fails to pass the profile retest and passes the test after replacement of spare parts. The profile accuracy of other blades all met the test indicators.
Table 4. Profile accuracy test results.

| Blade Number | Accuracy (mm) | First Test | Profile Retest | Note |
|--------------|---------------|------------|----------------|------|
| 1#-6#        | 0.3/0.5       | Pass       | Pass           | None |
| 7#-12#       | 0.3/0.5       | Pass       | Pass           | 7# blade fails to pass the profile retest and passes the test after replacement of spare parts |
| 13#-18#      | 0.3/0.5       | Pass       | Pass           | None |
| 19#-24#      | 0.3/0.5       | Pass       | Pass           | None |

3.2. Load simulation test

The propeller blade needs to bear a tension of more than 110N and a centrifugal force of more than 1000N under operating conditions. Therefore, after the propeller blade is manufactured and passes the profile test, the load simulation test is carried out. The test load should be 3 times greater than the working load. A fixed fixture was used to arrange the blade cantilever, and a clamping fixture was used to clamp the blade. A load is applied at the root, middle and tip of the blade to carry out the test. After the test, the flaw detection is tested and the profile precision was retested. It can be seen from Table 5 that after the load simulation test, breaking, cracking or other phenomena do not appear. The 7# blade fails to pass the profile retest and passes the test after replacement of spare parts.

Table 5. Load simulation test results.

| Blade Number | Root Loaded | Middle Loaded | Apex Loaded | Note |
|--------------|-------------|---------------|-------------|------|
| 1#-6#        | Pass        | Pass          | Pass        | None |
| 7#-12#       | Pass        | Pass          | Pass        | 7# blade fails to pass the profile retest and passes the test after replacement of spare parts |
| 13#-18#      | Pass        | Pass          | Pass        | None |
| 19#-24#      | Pass        | Pass          | Pass        | None |

3.3. Dynamic balance test

The unbalanced disturbance at high speed rotation may cause failure of the propeller and damage the driving motor. Therefore, after assembling the propeller blade and hub, it is necessary to test and correct the operation balance. The propeller products were tested by dynamic balance testing machine, the specimens were assembled in the cone rotor tooling to measure the unbalance, then modified by removing the hub material, the propeller products were retested until the requirements of dynamic balance grade were met. The dynamic balancing level is required to be G2.5, and the test speed is 2000rpm -3000rpm.

The test results are shown in Table 6, from which it can be seen that after correction, the final unbalance of each propeller meets the requirements.

Table 6. Dynamic balance test results.

| Propeller Number | Dynamic Balancing Level | Allowable Unbalance (gmm) | First Test Unbalance (gmm) | Final Unbalance (gmm) | Conclusion |
|------------------|-------------------------|---------------------------|---------------------------|-----------------------|------------|
| 1#               | G2.5                    | 0.91                      | 1.20                      | 0.55                  | Pass       |
| 2#               | G2.5                    | 0.91                      | 1.21                      | 0.76                  | Pass       |
| 3#               | G2.5                    | 0.91                      | 1.19                      | 0.64                  | Pass       |
| 4#               | G2.5                    | 0.91                      | 1.26                      | 0.58                  | Pass       |

3.4. Dynamic load test

In order to verify the manufacturing quality and safety performance of propeller products, it is necessary to carry out dynamic load test and conduct comprehensive assessment on the strength, stiffness and dynamic balance performance of propeller products. The high-power density power system was used for the test. The motor power was 15kW (Figure 5), the diameter was 85mm, the highest speed was
13000rpm, the control precision was 0.05%, and the supporting control system was shown in Figure 6. The test speed is 120% of the designed speed, and the test time for each speed is 30 min. The test results are shown in Table 7, from which it can be seen that the safety performance of the propeller product meets the standard under common torque and rotation speed.

![Figure 5. Motor of the power system.](image)

![Figure 6. Control system of the power system.](image)

### Table 7. Dynamic load test results.

| Hub Number | A  | B  | C  | D  |
|------------|----|----|----|----|
| Nominal Blade Angle | 0°  | 10°  | 20°  | -10°  |
| Measured Blade Angle | 0.1°  | 9.9°  | 20.1°  | -10.1°  |
| Speed (rpm) | The Test Results | Pass | Pass | Pass | Pass |
| 1000-4000 | Pass | Pass | Pass | Pass |
| 5000-8000 | Pass | Pass | Pass | Pass |
| 9000-13000 | Pass | Pass | Pass | Pass |
| Note | None | None | None | None |

3.5. *Propeller performance test*

Before the propeller product is put into operation, its aerodynamic performance shall be tested, and its load shall be calibrated by the performance test system. The performance test system is composed of the previous power system and a six-component measuring system. The measurement system is shown in Figure 7 and Figure 8, and the load of each component of the balance is shown in Table 8. The data
acquisition system is capable of anti-electromagnetic interference. Performance test examines the thrust, torque and efficiency of the propeller at various rotating speeds.

![Figure 7. Balance of the measurement system.](image1)

![Figure 8. Data acquisition system of the measurement system.](image2)

| Component     | Y  | X  | Mz | Z  | My | Mx |
|---------------|----|----|----|----|----|----|
| Load (N, Nm)  | 300| 400| 50 | 30 | 30 | 20 |
| Precision (%)  | 0.03| 0.01| 0.01| 0.03| 0.03| 0.04|
| Accuracy (%)   | 0.10| 0.07| 0.06| 0.07| 0.05| 0.07|

The test results are shown in Figure 9, Figure 10 and Figure 11. It can be seen from the figure that the propeller performance meets the requirements of the indicators.
Figure 9. Data map of the rotation speed and thrust.

Figure 10. Data map of the rotation speed and torque.

Figure 11. Data map of the rotation speed and efficiency.
4. Wind tunnel test results
After previous five tests, the propeller product meets the wind tunnel test conditions. The test is carried out in a 4-meter level wind tunnel, which can be seen in Figure 12. The propeller is used to simulate the thrust coefficient of seaplane under three flight conditions, listed in Table 9.

![Image](image_url)

**Figure 12.** 4-meter level wind tunnel test of the seaplane.

| Flight Conditions | Wind Speed(m/s) | Propeller Speed(rpm) | Blade Angle | Thrust Coefficient |
|-------------------|-----------------|----------------------|-------------|--------------------|
| Take off          | 32              | 12100                | -5°         | 0.2734             |
| Cruise            | 50              | 8950                 | -10°        | 0.0287             |
| Landing           | 40              | 12000                | -5°         | 0.1700             |

The test results are shown in Figure 13, Figure 14 and Figure 15. As can be seen from Figure 13, the repeatability precision of lift coefficient and drag coefficient of the test system is 0.00052 and 0.00049 respectively, which can reach the standard of engineering application. As can be seen from Figure 14, the variable torque performance of the propeller is good, and it can simulate the slipstream of the propeller under various working conditions. It can be seen from Figure 15 that the contribution of slipstream makes lift and drag increasing, and the longitudinal stability decreasing after Angle of attack 2. The test results show that the power simulation system composed of the propeller can study the slipstream influence of seaplane under various working conditions, and its data quality meets the standard of engineering application.
Figure 13. Data map of the repeatability precision of lift coefficient and drag coefficient.
Figure 14. Data map of slipstream influence of the propeller under various working conditions.
5. Conclusion
In this paper, the research and development process and quality control method of the composite material variable torque propeller used for wind tunnel power simulation, five tests and their detection results, as well as the wind tunnel test application are described in detail. The results show that:

1. Through the quality control method described in this paper, the propeller can be designed and manufactured to meet the technical specifications;
2. The power simulation system composed of the propeller can exert slipstream influence on a certain seaplane under various working conditions;

Figure 15. Data map of slipstream influence and unpowered conditions.
3. The quality of wind tunnel test data can meet the engineering application standards and meet the requirements of the study on the comprehensive influence of propeller power and sea surface effect of the aircraft.

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