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A New Algorithm on Automatic Trimming for Helicopter Rotor Aerodynamic Loads

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Abstract: In order to simulate the flight state of the helicopter effectively, it is necessary to trim the helicopter during the forward flight in a wind tunnel test. Previously, due to the lack of an internal-control closed loop in the test rig, the helicopter-wind-tunnel-test trimming was carried out manually, with low test efficiency, unstable data quality, and high labor intensity. With the continuous development of computer technology and automatic control technology, the helicopter-wind-tunnel-test trimming technology has been developing in the direction of automation and intelligence. The helicopter wind tunnel test automatic trimming system is a typical multi-input–multi-output (MIMO), strongly coupled, and complex nonlinear system, involving data acquisition and a processing system, rotor control system, tail-supported mechanism control system, wind-tunnel-speed pressure control system, and other subsystems, which is difficult to describe with an accurate mathematical model. Therefore, in order to meet the needs of a 3 m diameter rotor model aerodynamic performance evaluation and noise characteristics research wind tunnel test, an error feedback variable step automatic trimming algorithm is proposed based on the fuzzy-control principle to realize automatic trimming of aerodynamic loads of rotor model in the forward flight state. To verify the effectiveness and reliability of the trimming strategy, a series of wind tunnel tests on a 3 m diameter scaled rotor model of a helicopter were conducted in the FL-17 aeroacoustics wind tunnel of China Aerodynamics Research and Development Center (CARDC) based on the ϕ3m tail-supported helicopter rotor model wind tunnel test rig. The wind tunnel test's results show that the proposed automatic trimming algorithm has the characteristics of fast trimming speed and high efficiency, which can realize the automatic trimming of rotor model aerodynamic loads under different test states in the wind tunnel test effectively and reliably and greatly improve the intelligence level of helicopter wind tunnel test.

Keywords: rotor; helicopter wind tunnel test rig; fuzzy control; automatic trimming; wind tunnel test

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1. Introduction

Helicopters are aircraft that rely on the rotor blades to provide lift, create propulsion, and control force to achieve flight and maneuvering [1–3]. Compared with fixed-wing aircraft, helicopters are widely used in both military and civil applications because of their unique advantages, such as vertical takeoff and landing (VTOL), hovering, and strong maneuverability [4–6]. In recent years, with the rapid development of rotor aerodynamics, automatic control technology, and new material technology, as well as the continuous improvement of system integration, helicopter technology is developing new configurations and aiming for a higher performance and lower noise.

The helicopter wind tunnel test is a basic method for rotor aerodynamics research, which not only can provide crucial aerodynamic data for new helicopter development, but also is an important means to study helicopter aerodynamic noise and noise-reduction measures [7,8]. In recent years, although computational fluid dynamics (CFD) has made great progress, the aerodynamic characteristics of helicopters are very complex, and their aerodynamic forces have obvious nonlinear and unsteady characteristics [9,10]. The accuracy of the results of CFD calculation and analysis is low, but it is still insufficient to solve more complex engineering problems. Therefore, the wind tunnel test is still an important means to obtain helicopter aerodynamic data and evaluate helicopter performance.

When a helicopter is level flight in the air, all the external forces and moments acting on the helicopter are synthesized to zero [11,12]. Therefore, in order to simulate the flight state of the helicopter effectively, trimming is required during the helicopter forward-flight wind tunnel test. In 2003, Enns and Si of the Department of Electrical Engineering of Arizona State University proposed the direct neural dynamic programming (DNDP) algorithm to achieve trimming and trajectory tracking control of the small-scale helicopter [13,14]. Inspired by this algorithm, in 2004, Li from CARDC proposed to introduce neural network control technology into the helicopter-wind-tunnel-test trimming system, designed a neural network controller, trained and simulated it, realized the combined trimming control technology of manual trimming and neural network automatic trimming, and tested it in the helicopter forward flight wind tunnel test [15]. However, as the neural network is a learning algorithm, the neural network needs to be trained, and the training effect will directly affect the trimming quality and efficiency in the later wind tunnel tests [16]. Therefore, if one wants to improve the trimming quality and enhance the trimming efficiency of helicopter wind tunnel test, it is required that the network trained should approach and simulate the real model as closely as possible, which then leads to two more problems:

1. A large number of effective trimming test data are needed to train the neural network controller. In general, if the neural network wants to approach the real model accurately, it needs a large number of trimming data to train the neural network. The best trimming data for training the network are usually obtained by the wind tunnel test of the rotor model. If we use the trimming data of other rotor models or the trimming data of published standard models to train the network, it may lead to large trimming errors and a slow convergence rate in formal wind tunnel tests, which may not achieve real-time trimming and even lead to the dispersion of the trimming system;
2. Since the rotor models for each wind tunnel test are different (for the same helicopter wind tunnel test rig, generally the rotor aerofoil, chord length, number of propeller blades, etc., are different), the aerodynamic characteristics of each rotor model are also different, so the network needs to be retrained before each wind tunnel test, which will also lead to a more cumbersome process for each test.

In addition, the neural network automatic trimming in the helicopter wind tunnel test is not suitable for the whole test, mainly because a small wind velocity change will also lead to large rotor aerodynamic loads. Therefore, a neural network control algorithm cannot trim the rotor aerodynamic loads effectively with the change of wind velocity in time, and this may lead to excessive hub moments, thus damaging the test model and test equipment or causing other safety problems.

This paper proposes an error feedback variable step size automatic trimming algorithm based on fuzzy control to achieve dynamic trimming of aerodynamic loads in the forward flight state. In addition, based on the ϕ3m tail-supported helicopter rotor model wind tunnel test rig, the wind tunnel tests of a 3 m diameter scaled rotor model of a helicopter were successfully completed in the FL-17 aeroacoustics wind tunnel of CARDC by applying the automatic trimming algorithm proposed in this paper.

2. Trimming Principle of Helicopter Wind Tunnel Test

The helicopter forward-flight wind tunnel test is a test that uses the airflow generated by the wind tunnel to simulate the forward flight state of a real helicopter [17]. During the forward flight test, the rotor disc tilted forward in the direction of the inflow. As shown in Figure 1, let the wind tunnel airflow velocity be V, the rotor rotation velocity be Ω, and the axis inclination angle to be α. At this time, the airflow velocity at the blade tip of the advancing blade and the retreating blade is $\Omega R + V\cos\alpha$ and $\Omega R - V\cos\alpha$, respectively.

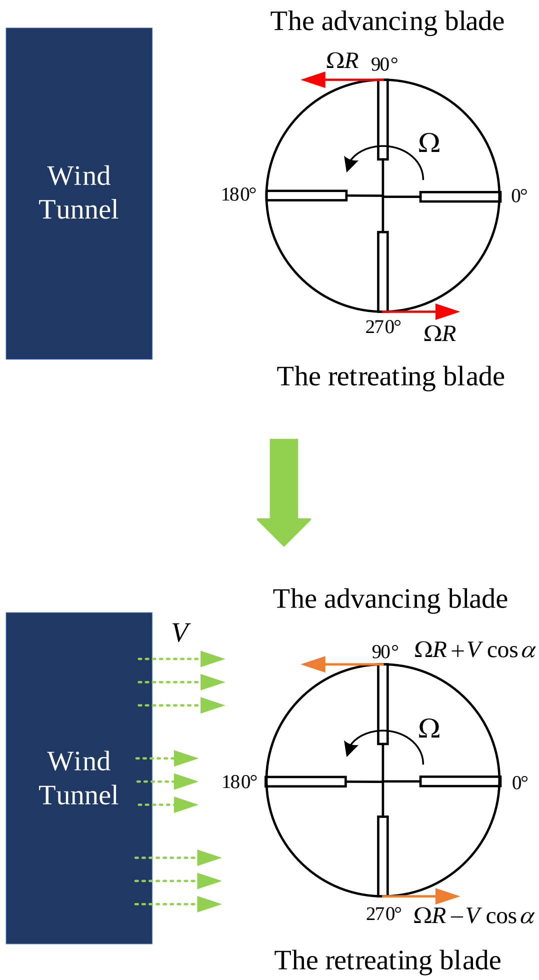

Figure 1. Trimming principle of helicopter wind tunnel test.

Due to the different airflow velocities, if the blade rotates at a fixed angle of attack, according to blade element theory, the lift generated by the advancing blade will be greater than that generated by the retreating blade. At this time, the rotor model will generate a large roll moment. In order to trim the roll moment, it is necessary to change the blade angle of attack cyclically, so that the helicopter model can reach the trimming state.

Helicopter-wind-tunnel-test trimming is the process of changing the rotor control angles, namely the collective pitch angle (θ_{col}), longitudinal cyclic pitch angle (θ_{lon}), and lateral cyclic pitch angle (θ_{lat}), by controlling the rotor control system and changing the axis inclination angle (α) by controlling the tail-supported mechanism based on the aerodynamic loads feedback, namely the lift coefficient (C_w), drag coefficient (C_h), rolling moment (M_x), and pitching moment (M_y) measured by the balance under the wind tunnel blowing condition, and finally achieving trimming to the given flight state. Among them, the given state generally refers to the flight state of the real helicopter, such as horizontal forward flight, inclined descent, etc. In addition, since the target flight state is given and the rotor control angles and the axis inclination angle are unknown, it is necessary to constantly adjust the rotor control system and the tail-supported mechanism according to the loads measured by the balance, so that C_w and C_h gradually approach the target state, and trim the M_x and M_y to zero or a very small value, so as to achieve the trimming state.

3. Automatic-Rotor-Load-Trimming Algorithm Based on Fuzzy Control

The helicopter-wind-tunnel-test trimming system is a complex nonlinear system with multiple inputs and multiple outputs [18–20] that involves not only the measurement and data acquisition of aerodynamic loads, but also the linkage and synchronization control of multiple motion-control systems, such as the rotor control system, the tail-supported mechanism, and the wind tunnel control system, and the system is difficult to implement. In addition, due to the different rotor models in each test, it is also impossible to establish a universally applicable automatic trimming control system, resulting in a significant loss of efficiency of the helicopter wind tunnel test. Therefore, the crucial problem to be solved in regard to the helicopter wind tunnel test is to design a trimming algorithm with good stability and robustness to improve the intelligent level of the test.

Based on the fuzzy-control principle, this paper adopts the error-feedback-variable step method to realize the automatic rotor-load trimming, which successfully solves the above problems. The reliability and effectiveness of the automatic trimming algorithm are verified through a wind tunnel test.

3.1. Introduction of Fuzzy-Control Automatic Trimming System

Fuzzy control is an advanced control strategy in recent control theory which is based on the basic idea of fuzzy mathematics and makes the control algorithm less complex, more adaptable, and more reasonable by simulating humans' fuzzy reasoning and comprehensive decision-making process; it is an important branch of intelligent control technology [21–23]. Traditional control methods are generally model based, while the helicopter-wind-tunnel-test trimming system is characterized as being multivariable, strong coupling, and nonlinear, making it difficult to describe with an accurate mathematical model. In contrast, fuzzy control does not depend on the plant model and can deal with the problem of accurate description and precise control of dynamic complex systems well [24–26].

The fuzzy-control automatic trimming system mainly consists of five parts: the trimming target, the controlled plant, the actuator, the sensor-and-measurement system, and the fuzzy controller. The structure diagram of fuzzy-control automatic trimming system is shown in Figure 2.

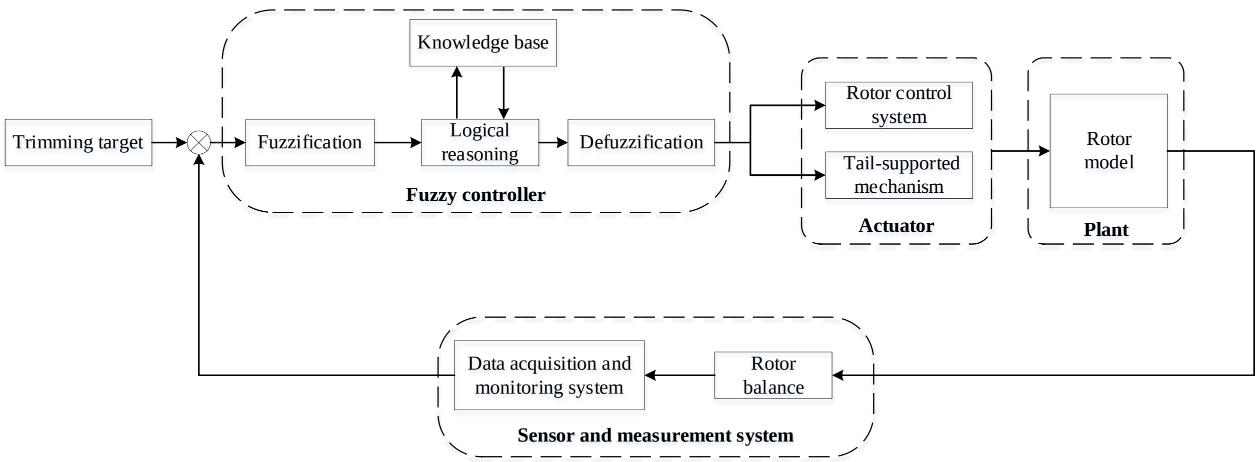

Figure 2. The structure diagram of the fuzzy-control automatic trimming system.

- The trimming target is a given desired value, which is determined by the test plan. It is generally the equilibrium state of the helicopter in stable flight.
- The plant is the rotor model, which is installed on the hub of the helicopter wind tunnel test rig.
- The actuator is mainly used to control the attitude of the rotor model, which is composed of the rotor control system and the tail-supported mechanism. The rotor control system changes the real-time angle of attack, θ, of the rotor model by controlling the ro-

tor control angles (θ_{col}, θ_{lon}, and θ_{lat}). At the same time, the tail-supported mechanism changes the axis inclination angle (α) of the helicopter wind tunnel test rig. Under the linkage control of the two systems, the aerodynamic forces and aerodynamic moments of the rotor model are finally changed.

- The sensor-and-measurement system consists of two parts: the rotor balance and the data-acquisition-and-monitoring system. The balance, as a sensor, is mainly used to measure the forces and moments generated by the rotor and convert them into analog signals. The data-acquisition-and-monitoring system acquires these analog signals, processes them, and finally calculates the aerodynamic loads (C_w, C_h, M_x, and M_y).
- As the core of the fuzzy-control automatic trimming system, the fuzzy controller mainly includes the processes of fuzzification, knowledge base, logical reasoning, and defuzzification. Fuzzification transforms the error, e, of the trimming target and the measurement feedback into the universe with appropriate rules, describes it with fuzzy variables, and calculates its corresponding membership. The knowledge base consists of a database and a rule base. The database contains the relevant definitions of data fuzzification and defuzzification. The rule base is a language-control rule that describes the control targets and strategies. In the automatic trimming algorithm, this rule is described in the form of a function cross-reference table. Logical inference is used to imitate the human mind to make a decision and apply fuzzy logic to make inferences to obtain the control signals described by fuzzy statements. The defuzzification, on the other hand, analyzes the fuzzy-control signals obtained by logical inference into specific control variables to realize the control of the plant. In the automatic trimming algorithm, the maximum membership method is used for defuzzification, where the fuzzy outputs of each component are first summed up and then inverse transformed into specific control values by the membership function.

3.2. Realization of Fuzzy-Control Automatic Trimming Algorithm

The procedure of automatic trimming based on fuzzy-control technology is as follows:

1. Obtaining the errors between the current model state and trim target as input: $\{\Delta C_w, \Delta C_h, \Delta M_x, \Delta M_y\}$;
2. Using the membership function to fuzzy the input data: $\left\{\mu_{C_w}, \mu_{C_h}, \mu_{M_x}, \mu_{M_y}\right\}$;
3. Deriving the output data according to the control laws: $\{\mu_{\theta_{col}}, \mu_{\theta_{lon}}, \mu_{\theta_{lat}}, \mu_{\alpha_r}\}$;
4. Obtaining the specific control values by defuzzing the output data: $\{\Delta\theta_{col}, \Delta\theta_{lon}, \Delta\theta_{lat}, \Delta\alpha\}$;
5. Repeating the above procedure until all trimming targets are achieved.

According to helicopter flight dynamics and control principle, the trim rules corresponding to load changes in the helicopter wind tunnel test can be inversely deduced (when wind velocity and rotor rotation velocity are fixed), as shown in Table 1.

Table 1. Trim rules corresponding to loads change in helicopter wind tunnel test. (In the table, ↑↑ represents more increment, ↑ represents less increment, ↓↓ represents more decrease, ↓ represents less decrease, and ○ represents basically unchanged.)

	θ_{col}	θ_{lon}	θ_{lat}	α
C_w (big)	↓↓	○	○	↑
C_w (small)	↑↑	○	○	↓
C_h (big)	↓	○	○	↑↑
C_h (small)	↑	○	○	↓↓
M_x (big)	○	○	↓↓	○
M_x (small)	○	○	↑↑	○
M_y (big)	↓	↓↓	○	○
M_y (small)	↑	↑↑	○	○

Taking the C_w trim rule as an example, the realization of the fuzzy-control automatic trimming algorithm is described in detail. Let the membership function of ΔC_w be Formula (1); the membership function plots is shown in Figure 3.

$$A(x) = \begin{cases} A_1, & x \geq 0.001 \\ A_2, & 0.0003 \leq x < 0.001 \\ A_3, & 0.00005 \leq x \leq 0.0003 \\ A_4, & -0.00005 < x < 0.00005 \\ A_5, & -0.0003 < x \leq -0.00005 \\ A_6, & -0.001 < x \leq -0.0003 \\ A_7, & x \leq -0.001 \end{cases} \quad (1)$$

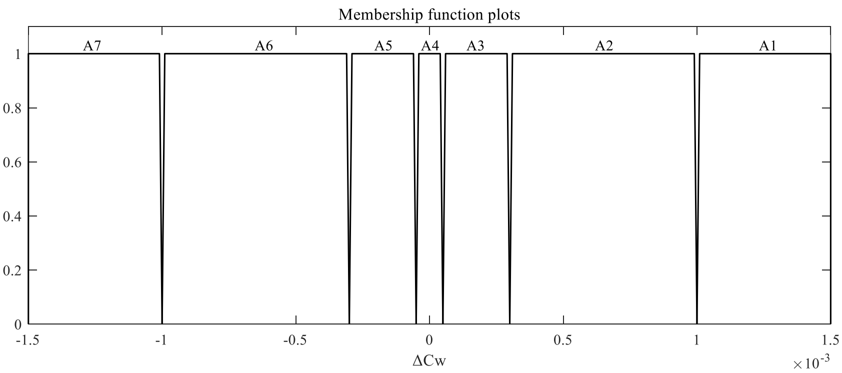

Figure 3. The membership function plots.

The fuzzy subset of input variable ΔC_w is A = {PB, PM, PS, O, NS, NM, NB}, corresponding to positive big, positive middle, positive small, zero, negative small, negative middle, and negative big. Similarly, the fuzzy subsets of output variables θ_{col} and α are B = {PB, PM, PS, O, NS, NM, NB}, which have the same meaning as the input variable. Moreover, the fuzzy-control rules of C_w trimming are shown in Table 2.

Table 2. Fuzzy-control rule table for C_w trimming.

	NB	**NM**	**NS**	**O**	**PS**	**PM**	**PB**
$\mu_{\theta_{col}}$	PB	PM	PS	O	NS	NM	NB
μ_α	NM	NS	O	O	O	PS	PM

If the current C_w is C_w = 0.006 and the specified trimming target is C_w = 0.010, then ΔC_w = 0.006 − 0.010 = −0.004, and the corresponding membership is $A(-0.004) = A_7$, which belongs to NB in the fuzzy subset. By querying Table 2, the output of fuzzification is $\mu_{\theta_{col}} = PB, \mu_\alpha = NM$. Let the inverse membership function of θ_{col} and α be as follows:

$$F(x) = \begin{cases} 0.1, & x = PB \\ 0.03, & x = PM \\ 0.005, & x = PS \\ 0, & x = O \\ -0.005, & x = NS \\ -0.03, & x = NM \\ -0.1, & x = NB \end{cases} \quad (2)$$

Then $\Delta\theta_{col}$ = 0.1 and $\Delta\alpha$ = −0.03, and to trim the given target, C_w, the collective pitch angle (θ_{col}) needs to be increased by 0.1°, and the axis inclination angle (α) needs to be decrease by 0.03°. After the actuator completes execution and moves to the response angle, repeat the trimming operation until the difference between the current state and the target state is less than the limit value. The fuzzy-control automatic trimming process is shown in Figure 4.

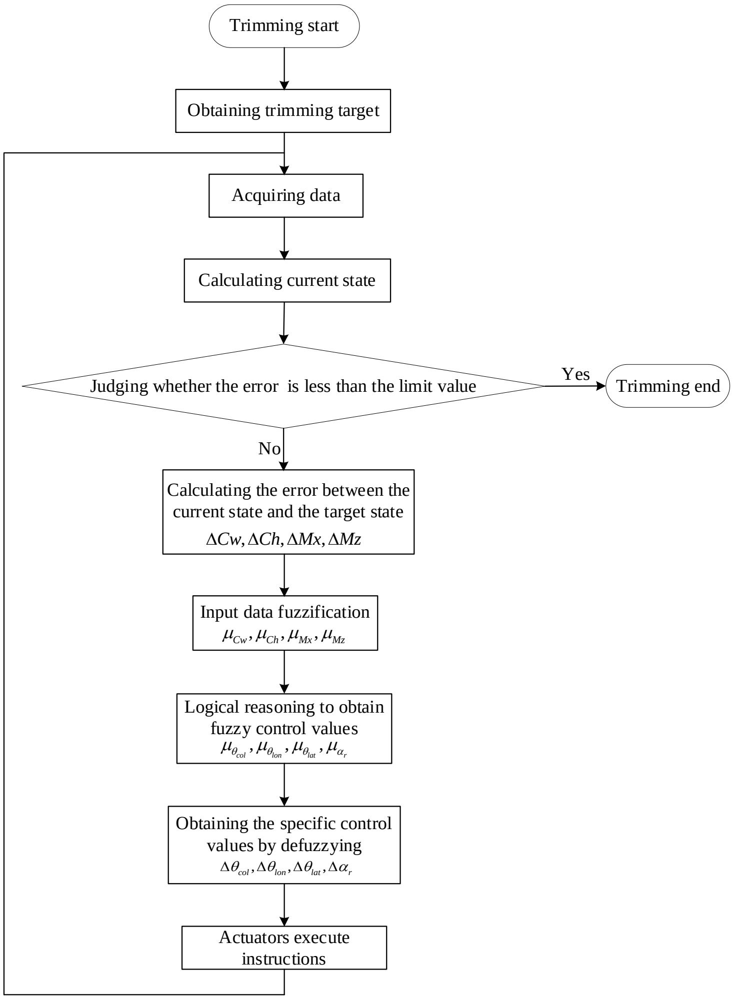

Figure 4. The fuzzy-control automatic trimming process.

4. Wind Tunnel Test

4.1. Wind Tunnel and Test Rig

The test was carried out in a CARDC FL-17 aeroacoustics wind tunnel. The wind tunnel is a low-turbulence reflux aeroacoustics wind tunnel. The test is conducted in an open test section with a size of 5.5 m × 4 m, the wind velocity range is 8 m/s~100 m/s; the open test section is shown in Figure 5. The background noise of the test section is 75 dBA~80 dBA, and the turbulence intensity of the open test section does not exceed 0.2%. The wind tunnel is equipped with multi-function model supported platform, acoustic measurement system, static pressure measurement system, force-measuring balance, and other equipment, mainly for the aeroacoustics test and aerodynamic test.

The test was conducted on the ϕ3m tail-supported helicopter rotor model wind tunnel test rig. The test rig mainly consists of the rig platform, power system, rotor control system, measurement system, data-transmission system, and other subsystems. The noise-test accuracy of the test rig is better than 0.8 dB, and the repeatability-measurement accuracy of the lift coefficient is better than 1.5%. During the test, the test rig is installed on the tail-supported mechanism of the wind tunnel, and the hub center is adjusted to be at the center of the wind tunnel through the tail-supported mechanism, as shown in Figure 6.

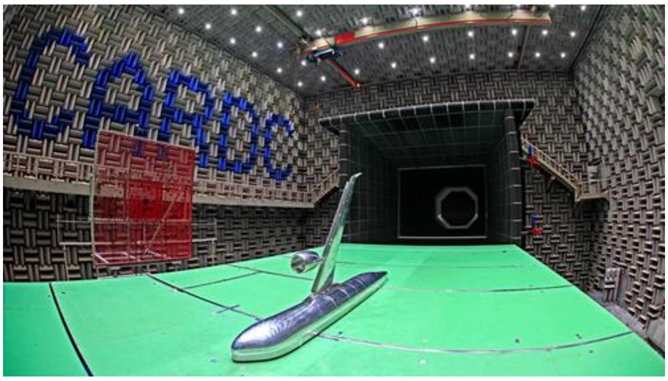

Figure 5. The CARDC FL-17 aeroacoustics wind tunnel.

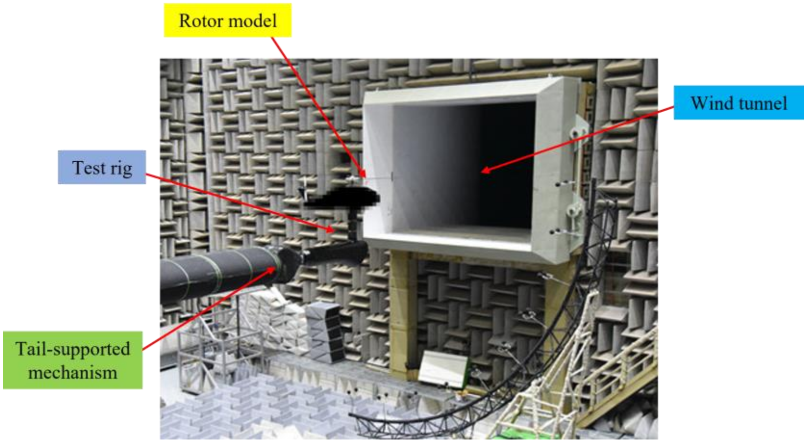

Figure 6. The ϕ3m tail-supported helicopter rotor model wind tunnel test rig.

4.2. Rotor System and Test Model

The rotor model is a 3 m diameter scaled rotor model with a hinge-less hub that has five blades installed on the hub. The shape of the blade tip is parabola swept back and tip sharpening. The rotor rotates counterclockwise from the top view. The structure of the rotor model is shown in Figure 7.

Figure 7. The structure of the rotor model.

4.3. Test Contents and Methods

4.3.1. Hover Test

The hover test is based on the principle of Mach number similarity at the rotor blade tip, changing the rotor collective pitch angle at a constant rotor rotation velocity in the test. The rotor aerodynamic loads and rotor power are measured by the rotor balance and torque balance, respectively, so as to obtain the rotor aerodynamic performance data.

In order to ensure the subsequent forward-flight-trimming wind tunnel test is carried out scientifically and the automatic-rotor-load-trimming algorithm is verified successfully, the stability and reliability of the ϕ3m tail-supported helicopter rotor model wind tunnel test rig and its subsystems were firstly evaluated by conducting three repetitive hover tests.

4.3.2. Forward-Flight Trimming Test

The forward-flight trimming test is a test that uses the airflow generated by the wind tunnel to simulate the real flight state of the helicopter in the air and trim the rotor aerodynamic loads through the rotor control system and the tail-supported mechanism. At this time, due to the combination of wind tunnel airflow and high-speed rotation of the rotor model, strong alternating loads will be generated on the rotor model. Compared with the hover test, the forward-flight trimming test is more complicated and the state is more dangerous. Therefore, according to the characteristics of helicopter wind tunnel test and considering the safety of the equipment, the wind tunnel power system, the rotor model wind tunnel test rig, the tail-supported mechanism, and the data-acquisition-and-monitoring system must follow a certain start–stop sequence when conducting the forward-flight trimming test. The specific test procedure is as follows:

1. The data-acquisition-and-monitoring system acquires the initial values of each channel;
2. When the rotor control angles (θ_{col}, θ_{lon}, and θ_{lat}) and the axis inclination angle (α) are all 0°, start the rotor to the target rotation velocity;
3. The rotor control system controls the rotor control angles (θ_{col}, θ_{lon}, and θ_{lat}) to the prefabricated angles;
4. The wind tunnel starts to run. During the process of wind velocity stabilization, the test participants use the helicopter wind tunnel test's automatic-rotor-load-trimming software to control the rotor control system to adjust the rotor control angles (θ_{col}, θ_{lon}, and θ_{lat}) in real time, according to the parameters displayed by the data-acquisition-and-monitoring system, so as to minimize the hub moments (pitch moment and roll moment) until the wind velocity reaches the target value and is stable;
5. After the wind velocity is stable, continue to use the helicopter wind tunnel test's automatic-rotor-load-trimming software to control the rotor control system and the tail-supported mechanism to adjust the rotor control angles (θ_{col}, θ_{lon}, and θ_{lat}) and the axis inclination angle (α) until the target state is reached and the required data are acquired;
6. Reduce the rotor collective pitch angle, θ_{col}, to the prefabricated angle, and gradually reduce the wind velocity of the wind tunnel. At the same time, pay attention to trimming the hub moments so that it does not change too much with the wind velocity. After the wind velocity is completely 0, reducing the axis inclination angle, α, and the rotor control angles (θ_{col}, θ_{lon}, and θ_{lat}) back to 0°, and the power system of the test rig stops.
7. Repeat the above procedure until all test items are completed.

4.4. Data Processing and Analysis

4.4.1. Hover Test

In the hover test, the rotor rotation velocity is 1400 rpm, and the range of the rotor collective pitch angle, θ_{col}, is 0~10°. Figure 8 shows the repeatability curves of aerodynamic coefficients (you can find them in Appendix A), such as C_T~θ_{col}, C_Q~θ_{col}, and C_Q~C_T, and the hover efficiency (FM) for the three hover tests.

It can be seen from Figure 8 that the maximum thrust coefficient is 0.01502, and the repeatability accuracy of the thrust coefficient, C_T, is better than 1.15%. The maximum torque coefficient is 0.001206, and the repeatability accuracy of the torque coefficient, C_Q, is better than 2.68%. The maximum hover efficiency is 0.7607, and the repeatability accuracy of the hover efficiency is better than 1.78%. The results of three hover tests show that the test rig and its subsystems are stable, reliable, and in good condition, which can meet the requirements of wind tunnel tests for forward-flight trimming and the verification of automatic-rotor-load-trimming algorithm.

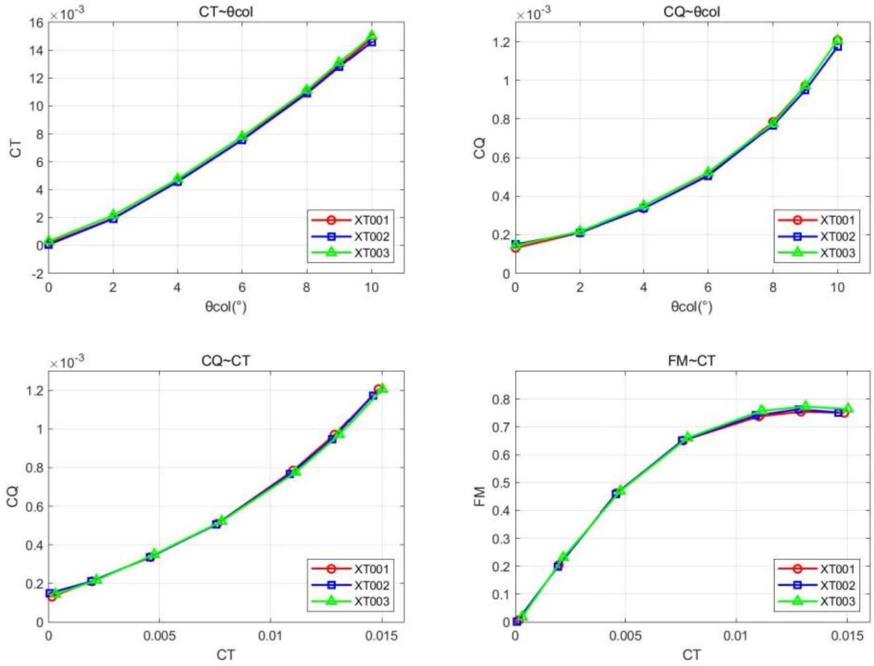

Figure 8. The repeatability curves of aerodynamic coefficients and hover efficiency of hover test.

4.4.2. Forward-Flight Trimming Test

The test participants conducted the forward-flight trimming test according to the test procedure, and the data results of one forward-flight trimming test are taken here for analysis:

- Test task: Complete the trimming of two test states, namely C_w = 0.0125 and C_h = 0.00030, and C_w = 0.0125 and C_h = 0.00072, at the given wind velocity.
- Test rotor rotation velocity: 1400 rpm.
- Test wind velocity: 33.8 m/s (obtained by forward ratio).

The results of the forward-flight trimming test are shown in Figure 9.

It can be seen from Figure 9 that 0~10 s is the test preparation stage, and the data-acquisition-and-monitoring system acquires the initial values of each channel. Then the rotor starts at 10 s and reaches the test rotation velocity of 1400 rpm at 74 s. At the same time, the rotor control system controls the rotor collective pitch angle, longitudinal cyclic pitch angle, and lateral cyclic pitch angle to prefabricated angles (θ_{col} = 3°, θ_{lon} = 1°, and θ_{lat} = −1°), and it reaches the prefabricated angle at 79 s. The wind tunnel starts blowing at 81 s and reaches the test wind velocity of 33.8 m/s at 153 s. During the process making the wind stable, the trimming system starts trimming at the same time to ensure that the pitching moment and rolling moment will not be too large and thus damage the test model. Finally, the lift coefficient (C_w) reaches the target value at 196 s, the drag coefficient (C_h) reaches the target value at 220 s, the pitching moment (M_y) and the rolling moment (M_x) reach the minimal value at 280 s, the first test state trimming is completed, and the data-acquisition-and-monitoring system acquires the test data; the rotor control angles are θ_{col} = 4.78°, θ_{lon} = 2.76°, and θ_{lat} = −2.98°, and the axis inclination angle is α = 0.74°. Next, start trimming the second test state on the basis of the first test state. The lift coefficient (C_w) of State 1 and State 2 is the same, so only the drag coefficient (C_h) needs to be trimmed. At 580 s, the drag coefficient (C_h) reaches the target value, and the pitching moment (M_y) and rolling moment (M_x) reach the minimum value at 749 s; the first test state trimming is completed; the data-acquisition-and-monitoring system acquires the test data; the rotor control angles are θ_{col} = 4.28°, θ_{lon} = 2.61°, and θ_{lat} = −3.06°; and the axis inclination angle is α = 2.75°. At 849 s, the wind tunnel stops, and the automatic trimming system follows the wind-speed change to adjust the rotor control angles to control the pitch moment and roll moment at a low level during the wind-velocity reduction to 0. At 923 s, the wind velocity in the wind tunnel decreases to 0. At this time, the rotor stops, and the axis inclination angle (α) and the rotor control angles (θ_{col}, θ_{lon} and θ_{lat}) are reduced back to 0° during the reduction of the rotor rotation velocity. At 985 s, the rotor rotation velocity returns to 0, and the test is completed.

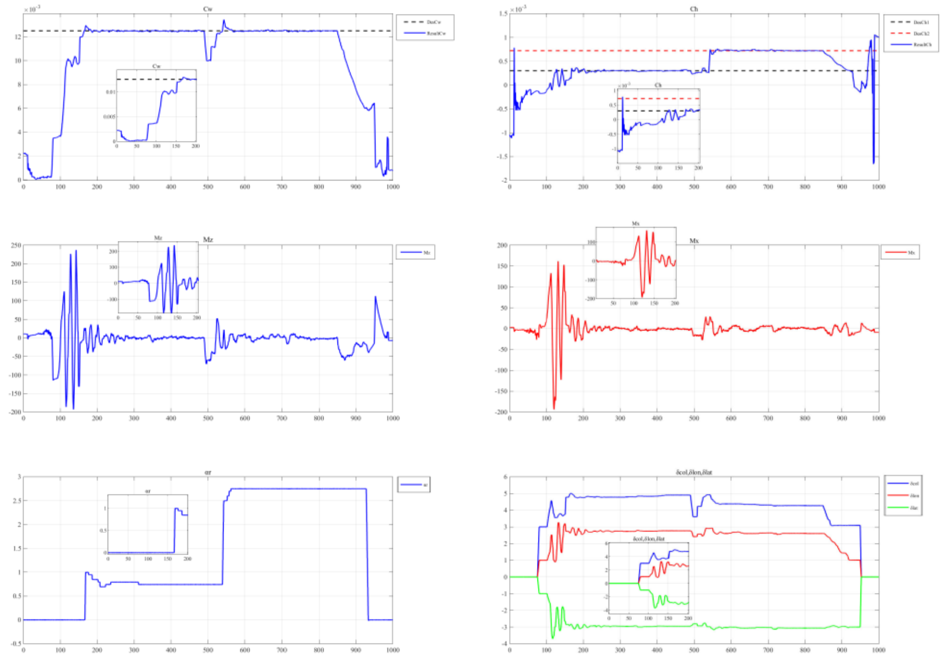

Figure 9. The results of the forward-flight trimming test.

The wind tunnel test's results show that the proposed automatic trimming algorithm can effectively and rapidly realize the automatic trimming of rotor model aerodynamic loads under different test states, and the trimming accuracy of the rotor model lift coefficient (C_w) and drag coefficient (C_h) is better than 0.5%, and the trimming accuracy of the pitch moment (M_y) and roll moment (M_x) is better than 3 NM.

5. Conclusions

Our research group carried out wind tunnel tests in the FL-17 aeroacoustics wind tunnel of CARDC based on the ϕ3m tail-supported helicopter rotor model wind tunnel test rig, using a 3 m diameter scaled rotor model. First, the test rig and its subsystems are examined through three repetitive hover tests. Then the error feedback variable step automatic trimming algorithm based on fuzzy control proposed in this paper is tested and verified through the forward-flight trimming test. The main conclusions are as follows:

1. From the data of the three repetitive hover tests, the repeatability of the thrust coefficient (C_T), torque coefficient (C_Q), and hover efficiency (FM) is good. The results show that the test rig and its subsystems are in good condition and can provide a stable and reliable platform foundation and hardware support for the forward-flight trimming test;
2. The results of the forward-flight trim test show that the proposed automatic trimming algorithm has the characteristics of fast trimming speed and high efficiency, and the single-point trimming time takes only 43 s. It can effectively and reliably achieve automatic trimming of rotor model aerodynamic loads under different test states, greatly improving the automation and intelligence of the helicopter wind tunnel test;

3. In the process of automatic trimming, the lift coefficient (C_w) and drag coefficient (C_h) trim faster, and the pitching moment (M_y) and rolling moment (M_x) trim slower. It can be concluded that the influence of rotor control on lift is greater than that on the drag, pitch moment, and roll moment, which is also consistent with the real helicopter flight control law.

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Appendix A. The Calculation Formulas of Normalized Aerodynamic Coefficients

In this paper, there are four normalized aerodynamic coefficients, namely the thrust coefficient, C_T; torque coefficient, C_Q; lift coefficient, C_w; and drag coefficient, C_h. The calculation formulas are as follows:

$$C_T = \frac{2T}{\rho\Omega^2 R^2 (\pi R^2)} \tag{A1}$$

$$C_Q = \frac{2M_k}{\rho\Omega^2 R^2 (\pi R^2) R} \tag{A2}$$

$$C_w = \frac{2L}{\rho\Omega^2 R^2 (\pi R^2)} \tag{A3}$$

$$C_h = \frac{2D}{\rho\Omega^2 R^2 (\pi R^2)} \tag{A4}$$

where ρ is the air density, Ω is the rotor rotation velocity, R is the rotor radius, M_k is the rotor torque, and T is the rotor thrust, as obtained through the hover test. The L and D are the rotor lift and drag, respectively, which are obtained through the forward-flight trimming test.

In addition, the normalized coefficient FM is namely the hover efficiency, and its calculation formula is as follows:

$$FM = \frac{C_T^{3/2}}{2C_Q} \tag{A5}$$

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