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Design of Flight Control System for a Small Unmanned Tilt Rotor Aircraft

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Abstract

A tilt rotor is an aircraft of a special kind, which possesses the characteristics of a helicopter and a fixed-wing airplane. However, there are a great number of important technical problems waiting for settlements. Of them, the flight control system might be a critical one. This article presents the progresses of the research work on the design of flight control system at Nanjing University of Aeronautics and Astronautics (NUAA). The flight control law of the tilt rotor aircraft is designed with the help of an inner/outer loop control structure and an eigenstructure assignment algorithm on the basis of a proper mathematical model already verified by the wind tunnel tests. The proposed control law has been born out through the construction of the flight control system and the flight tests. Now, the flight tests are still underway on a prototype of small unmanned tilt rotor aircraft. The results have evidenced the credibility of the aircraft design and the effectiveness of the flight control system for the tilt rotor working in the helicopter mode. A full envelope flight test is planned to carry out further researches on the flight control law.

Keywords: tilt rotor aircraft; control; aircraft models; flight dynamics

1. Introduction

A growing number of countries have been paying close attention to the development of tilt rotor aircraft, which combines the vertical lift ability of helicopters and the speed and range of fixed-wing airplanes[1-6] and has found wide applications in both military and civil fields.

The critical technological problem that is facing designers and researchers of tilt rotor aircrafts is design of flight control system. To find out the solution, a prototype of small unmanned tilt rotor aircraft has been designed and constructed, and a model for wind tunnel tests has been made to throw light on its aerodynamic performance. And the wind tunnel test results have been used to verify and improve the mathematical model. Based on this mathematical model, an inner/outer loop control structure and an eigenstructure assignment algorithm are used to design the tilt rotor flight control law. The proposed control law is verified through construction of a flight control system and accomplishment of flight tests, which are being underway.

The design of flight control law plays an significant role in future research on the development of this kind of aircraft. This article will make a concise introduction to the progresses of the work on it at Nanjing University of Aeronautics and Astronautics (NUAA).

2. Mathematical Modeling of Flight Dynamics

In modeling tilt rotor flight dynamics, as a tool of utmost importance, the aerodynamic model of rotor must include the aerodynamic model of aerofoil, the induced velocity model, and the blade flapping model. For the details of calculating the aerodynamic forces of a rotor, one can refer to Refs.[7-8]. In order to ensure the real-time calculation of a flight dynamics model, an aerodynamic interference coefficient is introduced to consider the disturbance between the rotor and the wing. According to the analysis of wind tunnel test results (see Fig.1) and calculated model results, the interference coefficient is reasonably chosen to be 0.87 for this model.

Assume that the aerodynamic model of the wing is rigid without elastic deformation. In the free wake, the aerodynamic force models of wing, fuselage, horizontal tail, vertical tail, and nacelle can be obtained from Ref.[9] while the method to calculate the aerodynamic

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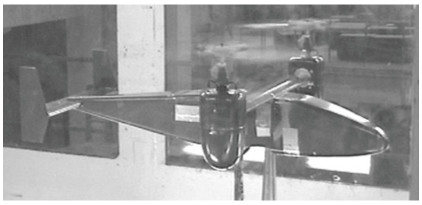


Fig.1 Wind tunnel test.

force model of the wing in the rotor-disturbed region from Ref.[10].

According to the above-cited modeling method, is built in the simulated environment of MATLAB/ SIMULINK a complete nonlinear flight dynamic mathematical model of the unmanned tilt rotor aircraft, of which the primary purposes are: ① to calculate the flight envelope of the tilt rotor and the conversion characteristics, etc., ② to acquire the linear model in the trim point to design the flight control system and analyze the control stability, and ③ to calculate the control response of the nonlinear model and evaluate the flying quality through the flight dynamic simulation.

In order to validate the flight dynamic mathematical model of a tilt rotor and ascertain its aerodynamic characteristics in flights in helicopter, airplane, and conversion modes (three modes of full envelope flight), as well as aerodynamical interference between components, have been planned and fulfilled wind tunnel tests (see Fig.1). Fig.2 shows the change of lift of an experimental aircraft with the pitch angle in an unpowered experiment when the nacelle angle is 90° and the wind speed 30 m/s. Fig.3 illustrates the change of the thrust of an experimental aircraft with the collective pitch in helicopter mode in a powered experiment when the nacelle angle is 90° and the wind speed is 0 m/s. Fig.4 shows the change of lift of an experimental aircraft according to pitch angle at the typical conversion point in a powered experiment when the nacelle angle is 60° , the wind speed 14 m/s, and the collective pitch 14° . Fig.5 displays the change of the thrust of an experimental aircraft with the collective pitch in a powered experiment when the nacelle angle is 0° and the wind speed 0 m/s. The minor differences between the test results and the theoretical results have attested to high reliability of the flight dynamic model of the tilt rotor developed by the authors, which could be applied well to flying quality evaluation and design of flight control system after further verification and modification.

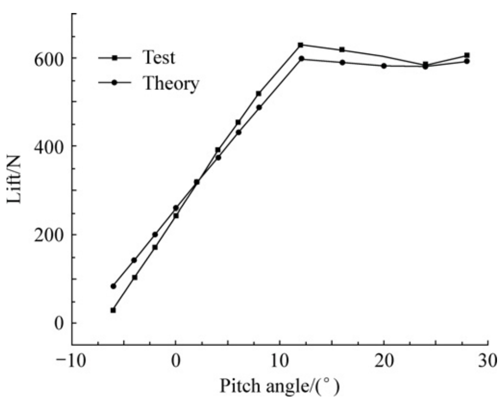


Fig.2 Change of lift with pitch angle (unpowered experiment, nacelle angle is 90° , and wind speed 30 m/s).

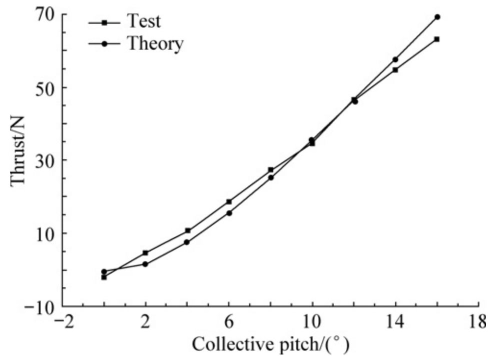


Fig.3 Change of thrust with collective pitch (powered experiment, nacelle angle is 90° , and wind speed 0 m/s).

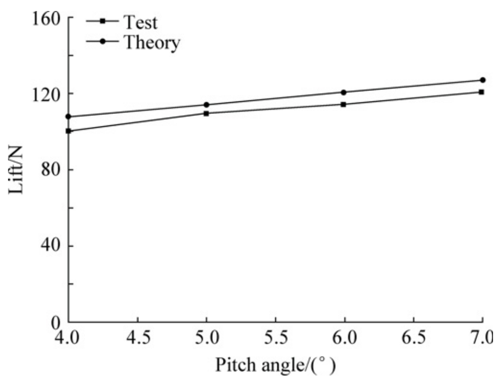


Fig.4 Change of lift with pitch angle at a typical conversion point (powered experiment, nacelle angle is 60° , wind speed 14 m/s, and collective pitch 14°).

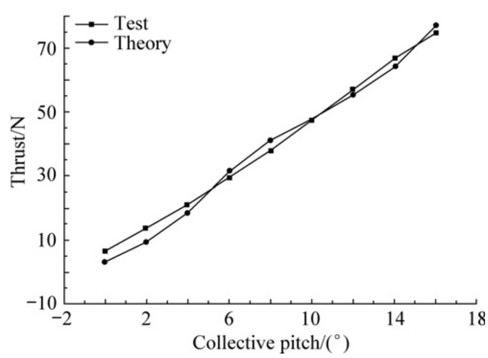


Fig.5 Change of thrust with collective pitch (powered experiment, nacelle angle is 0°, and wind speed 0 m/s).

3. Flight Control System Design

3.1. Conversion corridor

Conversion corridor is the sticking point in designing a control system. There are many choices available for the conversion corridor as lots of control interfaces exist. The problem is how to choose a proper path that ensures the safety and control simplicity in conversion. The principle of choosing conversion corridor in this example is described as follows: the pitch angle of an aircraft should make slow changes at low speeds. When the aircraft's forward speed gradually increases, as all of the control interfaces start working, the pitch angle could be kept fixed in the vicinity of a given value. This is done for two purposes: one is to make the conversion flight of the aircraft as stable as possible and the other is to provide guidance for designing the flight control system. The conversion characteristics should be optimized by the experience from flight-tests. Figs.6-7 indicate the theoretical trim results.

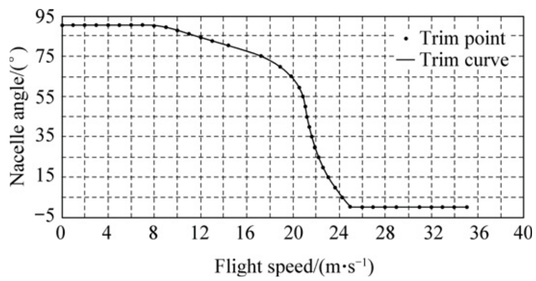


Fig.6 Nacelle angles against forward speeds.

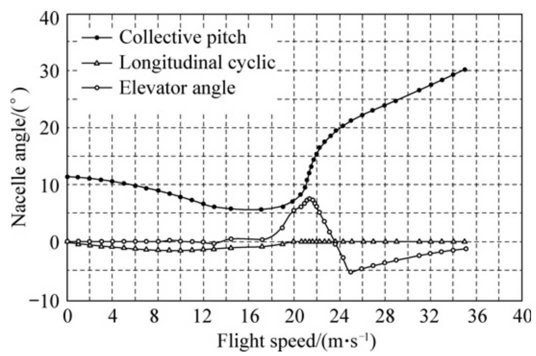


Fig.7 Trim control of conversion.

According to the calculated results of the flight dynamics model, it is known that the experimental aircraft is dynamically unstable in flight, which illustrates obvious changes of the dynamic characteristics in the conversion mode. As a very critical controlled-state variable in the full envelope flight, the attitude angle should be controlled and preserved to enable the unmanned tilt rotor aircraft to successfully accomplish the full envelope flight. The established and well-tried flight dynamic model makes it possible to adopt modern control theory to conduct the system analysis and synthesis. As a design method in the time domain, eigenstructure assignment with state feedback can assign the eigen-values and eigen-vectors to change the response of the system. A description of eigenstructure assignment is offered in Ref.[11].

The attitude control system of tilt rotors is made up of the inner/outer loop of the feedback control. The method is not only good for system decoupling and multi-mode control law design for this aircraft but also convenient for construction of the flight control system.

Fig.8 shows the structure of the inner/outer loop of feedback controller. In Fig.8, $\boldsymbol{r}_{\mathrm{m}}$ is reference input, $\boldsymbol{e}$ control error, $\boldsymbol{u}_{\mathrm{f}}$ system input, $\boldsymbol{y}_{\mathrm{c,inner}}$ inner loop output, and $\boldsymbol{y}_{\mathrm{c,outer}}$ outer loop output. The objectives and the technology of designing the inner loop and the outer loop are not the same. The inner loop mainly adopts state feedback combining the compensable matrix while the outer loop employs output feedback based on proportional and integral (PI) control. The inner loop makes the system decouple and improves the frequency response characteristics and stability and the outer loop pays attention to the control quality of the controlled variables. The inner loop regards the angular rate as controlled variables and the outer loop aims at the attitude control.

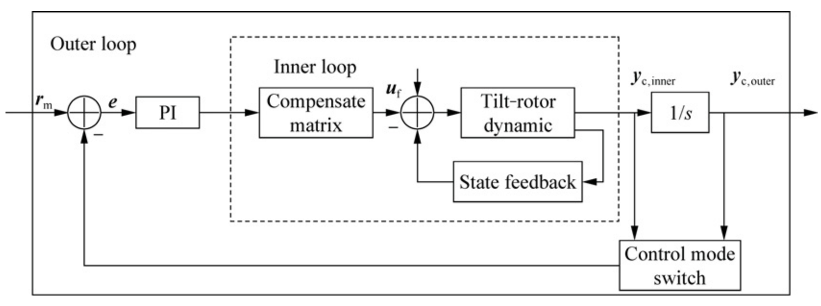


Fig.8 Structure of inner/outer loop of a feedback controller.

3.2. Inner loop design

The design of inner loop control views rate command attitude hold (RCAH) as the design objective and the outer loop control is used for design of attitude command attitude hold (ACAH). There is a simple integral relationship between the outer loop and the inner loop. When using both loops to design an attitude control system, the outputs of the inner and outer loops have a relationship as follows.

$$\begin{cases} \boldsymbol{y}_{\mathrm{c,inner}} = [w \;\; p \;\; q \;\; r]^{\mathrm{T}} & \text{(Output of inner loop)} \\ \boldsymbol{y}_{\mathrm{c,outer}} = [w \;\; \phi \;\; \theta \;\; r]^{\mathrm{T}} & \text{(Output of outer loop)} \end{cases}$$

where w is vertical velocity; p, q, and r are angular velocity components about fuselage x-, y-, and z-axes; and ϕ and θ roll angle and pitch angle, respectively.

The inner loop design includes state feedback and compensable matrix. Here, state feedback control is based on the eigenstructure assignment, the expected closed-loop eigen-values and eigen-vectors generated by the implicit model, which is abstracted from Ref. [12].

The four expected rate responses of the implicit model can be expressed as follows:

① The model of vertical velocity response

$$\frac{w(s)}{w_{\mathrm{c}}(s)}=\frac{\lambda_w}{s+\lambda_w} \tag{1}$$

② The model of roll rate response

$$\frac{p(s)}{p_{\mathrm{c}}(s)}=\frac{\lambda_p}{s+\lambda_p} \tag{2}$$

③ The model of pitch rate response

$$\frac{q(s)}{q_c(s)}=\frac{\lambda_q}{s+\lambda_q} \tag{3}$$

④ The model of yaw rate response

$$\frac{r(s)}{r_c(s)}=\frac{\lambda_r}{s+\lambda_r} \tag{4}$$

The coupling relationship between the forward speed and the pitch rate, and that between the side slip speed and the roll rate remain unchanged and can be expressed by

$$\frac{u(s)}{q_{\mathrm{c}}(s)}=\frac{\lambda_q}{s(s+\lambda_u)} \tag{5}$$

$$\frac{v(s)}{p_{\mathrm{c}}(s)}=\frac{\lambda_p}{s(s+\lambda_v)} \tag{6}$$

Eq.(5) can be rewritten into

$$\frac{u(s)}{q(s)}=\frac{u(s)}{q_{\mathrm{c}}(s)}\bullet\frac{q_{\mathrm{c}}(s)}{q(s)}=\left(1+\frac{\lambda_q}{s}\right)\bullet\left(\frac{1}{s+\lambda_u}\right) \tag{7}$$

In Eqs.(1)-(7), λ_w, λ_p, λ_q, λ_r, λ_u, and λ_v are desired eigen-values of transfer functions; u and v are forward and sideward velocity; and subscript "c" indicates control commands.

By transforming the above functions into the state space model ($\theta(s)=q(s)/s$), can be obtained

$$\dot{u}=-\lambda_u u+q+\lambda_q\theta \tag{8}$$

The differential equation of lateral velocity can be derived in the same way:

$$\dot{v}=-\lambda_v v+p+\lambda_p\phi \tag{9}$$

Eqs.(1)-(9) describe the expected models, which show the basic response type and expected flight dynamical performances of tilt rotor aircraft according to control performance requirements. λ_w, λ_p, λ_q, λ_r, λ_u, and λ_v can be confirmed based on control quality requirements.

The above expressions can be expressed in the general form as follows

$$\left.\begin{aligned}\dot{\boldsymbol{x}}&=\boldsymbol{A}_{\mathrm{d}}\boldsymbol{x}+\boldsymbol{B}_{\mathrm{d}}\boldsymbol{x}_{\mathrm{c}}\\ \boldsymbol{x}&=[u\ \ v\ \ w\ \ p\ \ q\ \ r\ \ \phi\ \ \theta]^{\mathrm{T}}\\ \boldsymbol{x}_{\mathrm{c}}&=[w_{\mathrm{c}}\ \ p_{\mathrm{c}}\ \ q_{\mathrm{c}}\ \ r_{\mathrm{c}}]\end{aligned}\right\} \tag{10}$$

where $\boldsymbol{x}$ is state vector of implicit model, $\boldsymbol{x}_{\mathrm{c}}$ input vector of implicit model, subscript "d" indicates desired matrices, and

$$\left.\begin{aligned}\boldsymbol{A}_{\mathrm{d}}&=\begin{bmatrix}-\lambda_u & 0 & 0 & 0 & 1 & 0 & 0 & \lambda_p\\ 0 & -\lambda_v & 0 & 1 & 0 & 0 & \lambda_p & 0\\ 0 & 0 & -\lambda_w & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & -\lambda_p & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & -\lambda_q & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & -\lambda_r & 0 & 0\\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0\end{bmatrix}\\ \boldsymbol{B}_{\mathrm{d}}&=\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ \lambda_w & 0 & 0 & 0\\ 0 & \lambda_p & 0 & 0\\ 0 & 0 & \lambda_q & 0\\ 0 & 0 & 0 & \lambda_r\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}\end{aligned}\right\} \tag{11}$$

In the model, parameters λ_w, λ_p, λ_q, and λ_r can be chosen according to the flying quality while parameter λ_u and λ_v only must be greater than zero to ensure the system stability. The expected closed-loop eigen-values and eigen-vectors can be obtained from the implicit model.

According to the expected eigen-values and eigen-vectors, the eigenstructure of the original system can be assigned by using eigenstructure assignment to acquire the state feedback gain K.

3.3. Outer loop design

After the inner loop design, the system becomes stable with an inner loop made of four independent loops characteristic of $[w\ p\ q\ r]^{\mathrm{T}}$. This paves a way for designing the outer loop design. Every channel of the outer loop can be designed separately. The structure of the outer loop of the longitudinal pitch angular velocity is shown by Fig.9, in which K_θ is the proportional gain of the pitch controller.

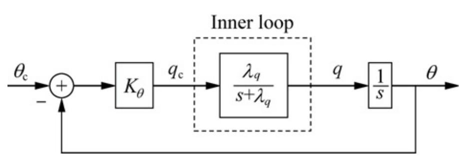


Fig.9 Structure of outer loop of pitch angle.

The transfer function of the pitch angle is

$$\frac{\theta(s)}{\theta_c(s)} = \frac{K_\theta \lambda_q}{s^2 + \lambda_q s + K_\theta \lambda_q} \tag{12}$$

The transfer function of the roll angle can be expressed likewise. And the transfer function of the yaw angle is

$$\frac{\phi(s)}{\phi_c(s)} = \frac{K_\phi \lambda_p}{s^2 + \lambda_p s + K_\phi \lambda_p} \tag{13}$$

where K_ϕ is the proportional gain of the roll controller.

In the above transfer functions, the parameters λ_p and λ_q have already been attained in the inner loop design and the parameters K_θ and K_ϕ should be determined by flight performance in the outer loop design. Figs.10-11 show the simulation results in the conversion mode, when the nacelle angle is 55°.

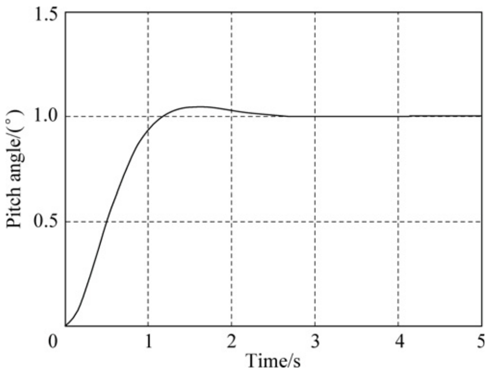


Fig.10 Pitch angle response under unit step pitch angle input (nacelle angle is 55°).

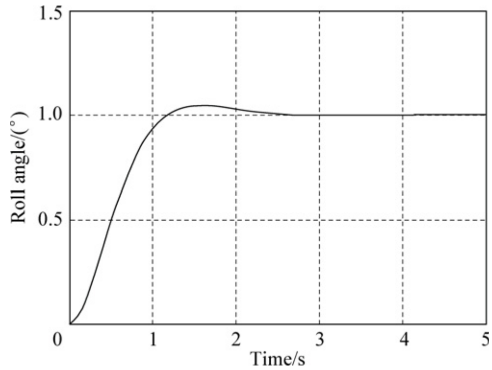
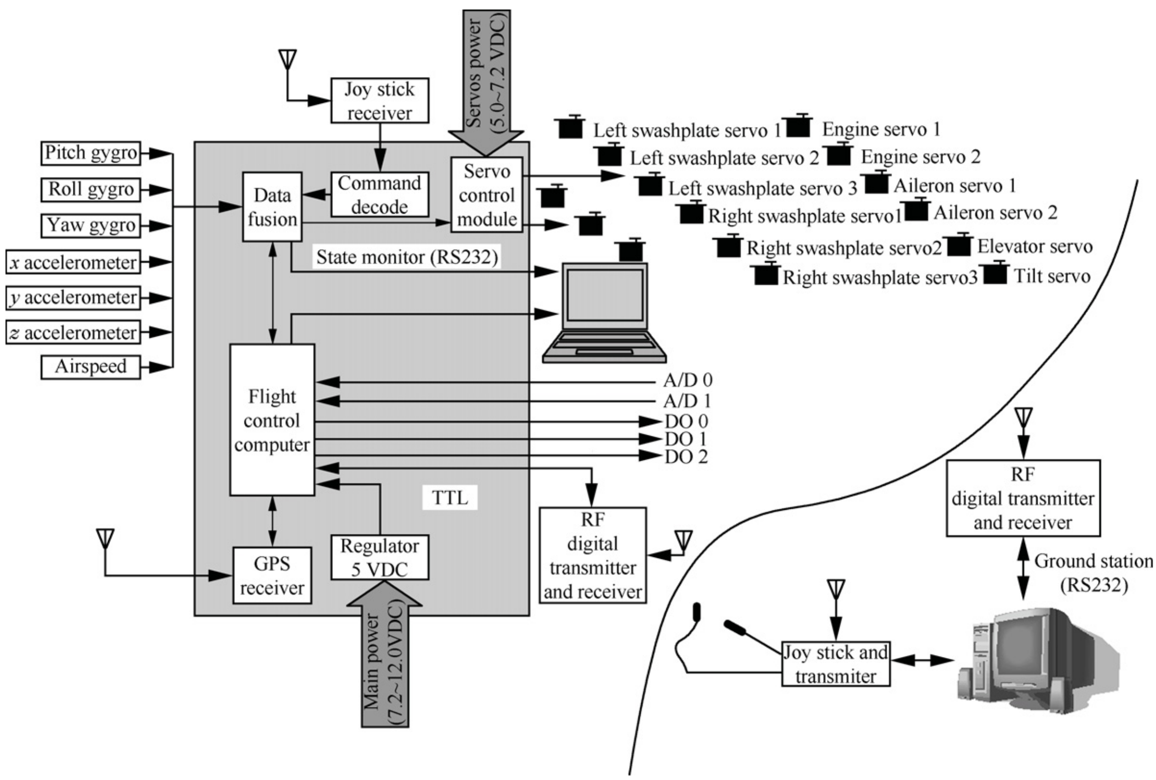


Fig.11 Roll angle response under unit step roll angle input (nacelle angle is 55°).

3.4. Construction of flight control system

The control system of the experimental tilt rotor includes a ground station and an airborne flight control system (see Fig.12).

The airborne flight system consists of a flight control computer, a servo control computer, a sensor system, GPS, a digital transmitter/receiver, and servos. The primary functions are: ① receiving control instructions from the ground station; ② guaranteeing the stability of the longitudinal, lateral, directional, and altitudinal channels and accomplishing closed-loop control of the longitudinal, lateral, directional, and altitudinal channels in helicopter mode, conversion mode, and airplane mode; ③ monitoring the airborne



Note: VDC—Voltage direct current; TTL—Transistor-transistor logic; RF—Radio frequency; DO—Digital out

Fig.12 Structure of control system.

system performance; ④ transmitting flight data to the ground station so as to replay, edit, and analyze them after the experiments; ⑤ controlling rotation speed of the engine; and ⑥ estimating the flight state of the unmanned tilt rotor aircraft.

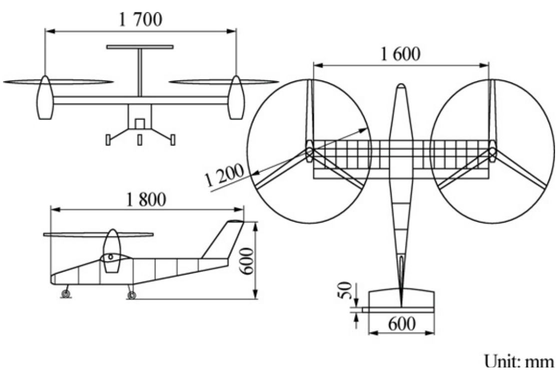
The ground station includes a joy stick, a ground station computer, and a digital transmitter/receiver. The joy stick serves the interface transmitting the operator's instructions; the ground station computer mainly monitors flight states; and the digital transmitter sends and the receiver receives commands and flight data.

4. Program of Experimental Research

In order to validate the proposed technology, a prototype of a small unmanned tilt rotor was chosen to be manufactured for reducing the research risk, shortening the research period, and saving the research cost. The flight speed of the experimental aircraft in airplane mode was minimized enough to satisfy the requirements for visual manipulation in initial flight tests. Technically ripe engine, actuator, and others were adopted to ensure the planned research progress rate and reliability. Full use of existing testing conditions was made to verify every technological detail of the experimental aircraft with the purpose of realizing vertical taking-off and landing, hovering in helicopter mode, and flying in conversion mode and airplane mode.

During the general design of the unmanned tilt rotor, a normal high-wing layout was adopted. The flaps and ailerons were integrated into the wing and two tilt nacelles were fitted outboard of the wing. The horizontal and vertical tails, elevator, and rudder were arranged on the tail. A tricycle landing gear was chosen. Two engines were used to drive two sets of rotors through a synchronous shaft to coordinate the rotational speeds of both rotors. A digital position control system with a worm gear and worm mechanism provided the required moments for tilting the nacelles. Fig.13 illustrates the aerodynamic configuration of the aircraft.

The ongoing research program of the experimental aircraft includes the structure tests of the aircraft, the tests of the rotor and the engine on the ground, simulation of flight control system on the ground, and flight



(a) Three views

(b) Photo

Fig.13 Three views and a photo of experimental aircraft.

tests (see Fig.14). From the successful flight tests, it can be concluded that the control trim point shown in Fig.7 is reasonable.

(a) Helicopter and take off

(b) Conversion

Fig.14 Flight test photos.

5. Conclusions

This article presents a flight control system of a small unmanned tilt rotor aircraft based on an improved mathematical model that has been validated in flight tests. The following conclusions can be drawn:

(1) The small unmanned tilt rotor aircraft developed by authors is fit for attesting to the critical technology which includes flight dynamic modeling and flight control system design.

(2) The results of the wind tunnel test have evidenced the viability of the tilt rotor flight dynamic model. Based on this mathematical model, the conversion corridor of the tilt rotor is derived. The flight control system is analyzed and synthesized by using an eigenstructure assignment control algorithm and the inner/outer loop control structure.

(3) Flight tests of the tilt rotor aircraft have been successfully carried out. The results have born out the

credibility of the aircraft design and the effectiveness of the flight control system in controlling the tilt rotor in helicopter mode.

(4) A full envelope flight test is planned to research the flight control law.

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Erratum to "Uniform Coverage of Fibres over Open-contoured Free-form Structure Based on Arc-length Parameter" [Chinese Journal of Aeronautics 21(2008)571-577]

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It is regretted that the author corrections requested at the proof stage were not made accurately. There are some incorrect typings in two equations which will lead to inaccurate results if readers perform calculations directly with them.

Actually , the vector "$\boldsymbol{N}(s)$" in equations (8) and (12) should be changed into "$\boldsymbol{S}_u \times \boldsymbol{S}_v$".

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