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Design and application of an Electric Tail Rotor Drive Control (ETRDC) for helicopters with performance tests

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Abstract With the development of electric helicopters' motor technology and the widespread use of electric drive rotors, more aircraft use electric rotors to provide thrust and directional control. For a helicopter tail rotor, the wake of the main rotor influences the tail rotor's inflow and wake. In the procedure of controlling, crosswind will also cause changes to the tail disk load. This paper describes requirements and design principles of an electric motor drive and variable pitch tail rotor system. A particular spoke-type architecture of the motor is designed, and the performance of blades is analyzed by the CFD method. The demand for simplicity of moving parts and strict constraints on the weight of a helicopter makes the design of electrical and mechanical components challenging. Different solutions have been investigated to propose an effective alternative to the mechanical actuation system. A test platform is constructed which can collect the dynamic response of the thrust control. The enhancement of the response speed due to an individual motor speed control and variable-pitch system is validated.

1. Introduction

In analogy with the aircraft electrification trend referred to as the More Electric Aircraft (MEA) approach, helicopters propulsion and their flight control devices are also experiencing a system optimization by the adoption of electric actuators.[1–2] Envisioned benefits for the development of electrically powered alternatives to hydraulically, pneumatically, or mechanically powered systems are: optimization of the power distribution,[3,4] easier and reduced maintenance due to the unified and simplified integration,[5,6] standardization of components,[7,8] new solutions and potential architectures not available before,[7,9] reduced noise generated by the tail rotor; reduced take-off weight.[10,11]

In this paper, one challenge is the development of a direct-drive Electrical Tail Rotor Drive Control (ETRDC) system[12] in replacement of the traditional actuation system that receives power by means of torque tubes and gearboxes.

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The main task for a tail rotor is to counteract the torque generated by the main rotor, and thus strong reliability and safety requirements for a tail rotor is in the first place of its design. Moreover, a direct-drive actuation system shall be installed in the tail with strict constraints in terms of size and weight.

Permanent Magnet (PM) motors[13] represent a promising solution to achieve high power density, and they exhibit well-known features such as high efficiency and good operating performance.

Most of the motor-driven lift components are used on quadrotors. The electric propulsion system of a typical UAV includes the following components: (A) blades, (B) a gear-box (optional), (C) a cooling system (optional), (D) an electric motor, (E) a driver, (F) an energy source, (G) wiring, plugs, and connectors. Most of the systems do not own blades of a large size.[14] Traditional methods for blade design are based on the well-known work by Betz and Prandtl from 1919,[15] and such an optimized design was equipped in Rutan's Voyager.[16,17]

Bouabdallah and Siegwart[18] has described a method for iteratively designing a vehicle with a maximum limitation of mass and length to achieve a desired thrust-to-weight ratio. The method requires a database of actuators, batteries, and airframe components to calculate the total mass. Bershadsky et al.[4] has presented a database which parameterizes drive components to meet the need of design and optimization.

Generally, the control of thrust of small electric aircraft is realized by adjustment of the rotational speed of motors.[19] The aerodynamic interference between a helicopter's main rotor and tail is complex, and the alternating load and flight direction of its fuselage makes its aerodynamic condition rigorous.

This paper presents a new contracted structure application on ETRDC with the purpose of accelerating the aerodynamic control response. A comparison with the traditional variable pitch tail structure is carried out, and a detailed design process and parameters are proposed.

Under the constraints of weight and volume, a direct pitch control actuator is developed in order to eliminate the number of transmission mechanisms. A test was conducted to verify the speed of control response, and the time consumption from one thrust level to another is about 80% less.

2. Parameterization of drive, control, and lift components

The main dimension of a helicopter is shown in Fig. 1. l is the distance between the main shaft and the center of the tail rotor, R_{HB} is the radius of the main rotor, R_{TR} is the radius of the tail rotor, and $\varepsilon R_{\mathrm{TR}}$ is the distance between the main rotor tip and the center of the tail rotor. The maximum take-off weight is 230 kg, and the subsequent examples are calculated based on this aircraft.

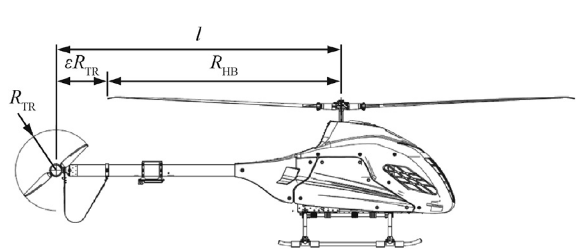

Fig. 1 Nomenclature of fuselage.

2.1. Tail rotor power

Considering the loss caused by the fuselage and the helicopter maneuver reserve factor, the moment balance equation is described by

$$T_{\mathrm{TR}} l = \zeta_{ynp} M_{\mathrm{HB}} \tag{1}$$

where T_{TR} is the thrust of the tail rotor, M_{HB} is the torque of the main rotor, and ζ_{ynp} is the maneuver reserve factor. The induced power of the main rotor P_{IND} can be described by

$$P_{\mathrm{IND}} = T_{\mathrm{HB}} v_{\mathrm{i}} \tag{2}$$

where T_{HB} is the main rotor thrust, and the relationship between the induced power and required power of the rotor can be described by

$$P_{\mathrm{IND}} = P \eta_{\mathrm{OHB}} \tag{3}$$

where η_{OHB} is the efficiency of blades, and P is the required power of the main rotor. The relationship[20] between the induced velocity v_{i} and the main rotor thrust T_{HB} can be described by

$$v_{\mathrm{i}} = \sqrt{\frac{T_{\mathrm{HB}}}{2\rho A}} \tag{4}$$

Therefore, the relationship between the main rotor thrust and the induced power can be calculated by

$$T_{\mathrm{HB}} = \left(\sqrt{2\rho \Delta \pi R_{\mathrm{HB}}^2} P \eta_{\mathrm{OHB}}\right)^{2/3} \approx \left(1.39\sqrt{\Delta} D P \eta_{\mathrm{OHB}}\right)^{2/3} \tag{5}$$

where A is the rotor disk area, ρ is the air density, 1.225 kg/m^3, $\Delta = \rho_0/\rho$ is the relative density of altitude, D is the diameter of the main rotor disk, and $\eta_{\mathrm{OHB}} = 0.7 - 0.8$ is the efficiency of blades.[21,22]

The relationship between T_{HB} and the gravity of the whole fuselage G can be described by

$$T_{\mathrm{HB}} = \zeta_{O\delta\alpha} G \tag{6}$$

where $\zeta_{O\delta\alpha}$ is the blowing loss of the main rotor.

The relationship between the torque of the main rotor M_{HB} and the disk load of the main rotor w_{DHB} can be described by

$$M_{\mathrm{HB}} \omega_{\mathrm{HB}} \cdot \frac{60}{2\pi} = 9.55 \frac{P_{\mathrm{IND}}}{\eta_{\mathrm{OHB}}} = 6.101 \frac{\zeta_{O\delta\alpha}^{3/2}}{\eta_{\mathrm{OHB}}} \sqrt{w_{\mathrm{DHB}}} \frac{1}{\sqrt{\Delta}} \tag{7}$$

Substituting Eq. (1) into Eq. (7), we obtain

$$T_{\mathrm{TR}} = 0.638 \zeta_{ynp} \zeta_{O\delta\alpha} \frac{G\sqrt{w_{\mathrm{DHB}}}}{\sqrt{\Delta} \eta_{\mathrm{OHB}} l \omega_{\mathrm{HB}}} \tag{8}$$

where ω_{HB} is the rotational speed of the main rotor (rad/s).

Substituting Eq. (5) into Eq. (8), we obtain

$$P_{\mathrm{TR}} = 0.183 \zeta_{ynp}^{3/2} \zeta_{O\delta\alpha}^{3/2} \frac{G^{3/2} w_{\mathrm{DHB}}^{3/4}}{\eta_{\mathrm{OHB}}^{3/2} l^{3/2} \omega_{\mathrm{HB}}^{3/2} \Delta^{5/4} R_{\mathrm{TR}} \eta_{\mathrm{OTR}}} \tag{9}$$

where $\eta_{\mathrm{OTR}} = 0.6$–$0.7$ is the efficiency of the tail rotor.

Substituting Eq. (5) into Eq. (6), we obtain

$$P_{\mathrm{HB}} = \frac{\zeta_{O\delta\alpha} G \sqrt{w_{\mathrm{DHB}}}}{1.56 \eta_{\mathrm{OHB}} \sqrt{\Delta}} \tag{10}$$

The relative required power consumption of the tail rotor can be obtained from

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