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GENERAL PARAMETERS DESIGN METHOD OF CANARD ROTARY WING AIRPLANE UNDER THE INFLUENCE OF POWER SYSTEM

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Abstract

Canard rotary wing(CRW) airplane is a VTOL aircraft which has a helicopter mode and a fixed wing mode. The aircraft can take off and land as a helicopter in helicopter mode ,In fixed wing mode the aircraft can carry out high speed flight and cruise efficiently. Power demand of the helicopter mode and fixed wing mode are different, so the engine operates at two different points when the CRW airplane is powered by only one engine. The two operating points need to meet the high power demand during take-off period and the low power and low specific fuel consumption requirements during cruise period.

This paper describes an aircraft and engine matching method of single-powered canard rotary wing airplane to maximize efficiency and range. The interaction between the general parameters of the CRW airplane and difficulties in single-powered CRW airplane design are analysed. An experimental study is conducted to investigate performance characterization of an 2-stroke piston engine. It can be concluded that the ratio of helicopter mode required power and fixed wing mode required power must be within a reasonable range when the CRW airplane is powered by one engine and CRW airplane's lowest cruising speed is limited by engine characteristics. Making the required power of helicopter mode be equal to engine's maximize power and making the required power of fixed wing mode be equal to engine's economical power will be a good match. This paper design an 100kg level airplane as an example to match the general parameters with the engine to meet the needs of engine working stability and cruising economically. The matching method is also suitable for other types of VTOL.

Nomenclature

C_T	=	tension coefficient
C_q	=	torque coefficient
m	=	airplane mass
P_h	=	helicopter mode hovering power
P_w	=	fixed wing mode cruising power
n_h	=	$\frac{m}{P_h}$,helicopter mode power loading
n_w	=	$\frac{m}{P_w}$,fixed wing mode power loading
v	=	helicopter wingtip's speed
p_1	=	helicopter rotor disc loading
p_2	=	fixed wing wing-loading
ρ	=	air density
a	=	speed of sound
K_Δ	=	weight coefficient
V	=	speed of airplane
S	=	wing area
C_L	=	0.4836,lift coefficient at maximum lift-drag ratio
g	=	gravitational acceleration
C_d	=	drag coefficient at maximum lift-drag ratio
G	=	gravity
E	=	lift-drag ratio
ρ_{3000}	=	0.9093,air density at 3000 meters height
A	=	rotor disk area
R	=	rotor radius

1 Introduction

CRW airplane is a special aircraft which can take off and land as a helicopter in helicopter mode and cruise as a fixed wing aircraft in fixed wing mode[3]. CRW airplane has three wings: canard, main wing and horizontal tail. Canard and horizontal tail is fixed, but the main wing can rotate at high speed as a rotor in helicopter mode and become a fixed wing when it is locked in fixed wing mode.

Because both main wing and propeller need power to be driven, CRW airplane has many forms of power system to choose from. Such as: separately using two engines for main wing and propeller(double-powered system), only using one engines for main wing and propeller(single-powered system) and gas-electric hybrid system. Double-powered system is easy but will bring dead weight. Gas-electric hybrid system is efficient but complicated. Single-powered system is easyer than gas-electric hybrid system but the matching of aircraft and engine is difficult. Power demand of the helicopter mode and fixed wing mode are different, so the engine operates at two different points when the CRW airplane is powered by single-powered system. As the engine has different fuel consumption and stability in different operating point, the engine can't work or have a big specific fuel consumption(SFC) at some output power. Power demand of the helicopter mode and fixed wing mode have a big gap or the engine and the two modes of the aircraft matching unreasonably will lead to poor aircraft economy, engine working in a state of instability or dangerous situations. So we need a comprehensive design of the aircraft's fixed wing mode and helicopter mode combined with engine characteristics to make the engine run economically and steadily in the both modes of CRW airplane.

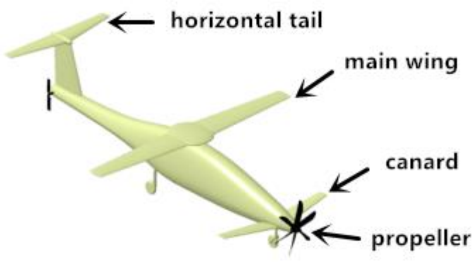

Fig.1. Canard rotary wing airplane

Fig.2. Canard rotary wing airplane model

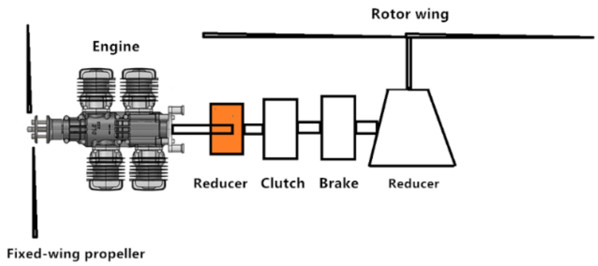

Fig.3. Driving mode of single-powered system

2 Calculate the required power

Based on the previous research for the canard rotary wing airplane, the required power of the helicopter mode and the fixed wing mode is calculated.

2.1 The required power of helicopter mode

An experimental study is conducted to investigate the relationship between tension coefficient and torque coefficient of the main wing under different helicopter wingtip's speed. The result is presented in Fig.4.

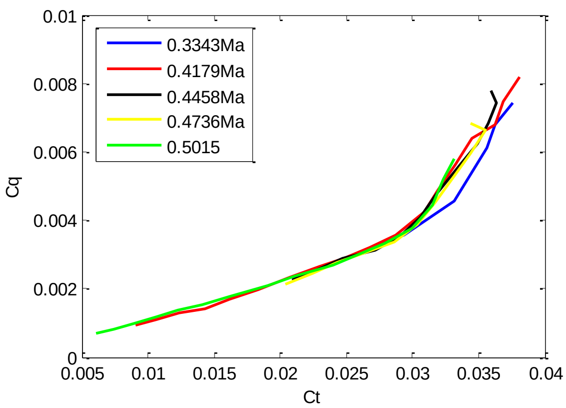

Fig.4

According to the theory of rotor and Fig.4, we can get the relationship between helicopter hovering power loading、helicopter wingtip's speed and tension coefficient as follow:

$$0.6501C_T^{1.5}+0.000375-0.002828\frac{C_T}{v}\frac{\frac{1000}{9.8}}{\frac{m}{P_h}}=0 \quad (1)$$

And because helicopter rotor disc loading can be expressed as follow:

$$p_1=\frac{\frac{1}{2}\rho(v\,a)^2C_T}{K_\Delta} \quad (2)$$

The n_h-p_1 curve under different helicopter wingtip's speed is shown in Fig.5

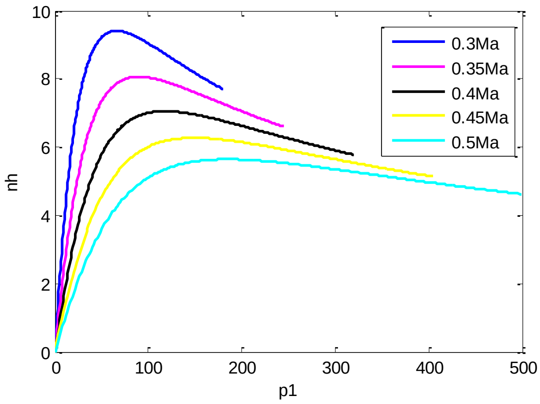

Fig.5

From Fig.5, we can get that the helicopter mode can reach the maximum hovering power loading of 9.4.

2.2 The required power of fixed wing mode

According to the previous wind tunnel test, we can get the lift-drag ratio of the fixed wing mode of the canard rotary wing airplane:

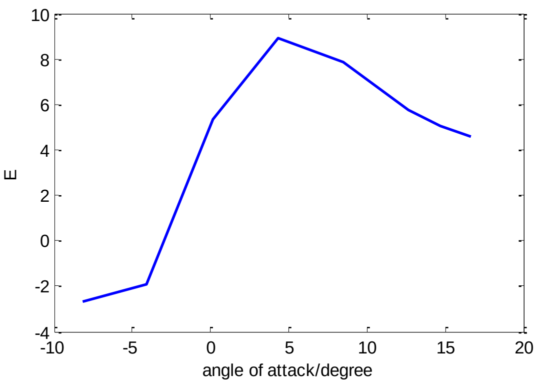

Fig.6.lift-drag ratio of the fixed wing mode

According to the fixed wing power loading formula:

$$n_w=\frac{\frac{1}{2}\rho V^2SC_L/g}{\frac{1}{2}\rho V^2SC_dV/1000}=\frac{1000E}{Vg} \quad (3)$$

And fixed wing wing-loading formula[1]:

$$p_2=\frac{G}{S}=\frac{\frac{1}{2}\rho V^2SC_L}{S}=\frac{1}{2}\rho V^2C_L \quad (4)$$

So

$$n_w=\frac{1000E\sqrt{\rho_{3000}C_L}}{g\sqrt{2p_2}} \quad (5)$$

Draw the n_w-p_2 cure when cruising at the maximum lift-drag ratio in Fig.7

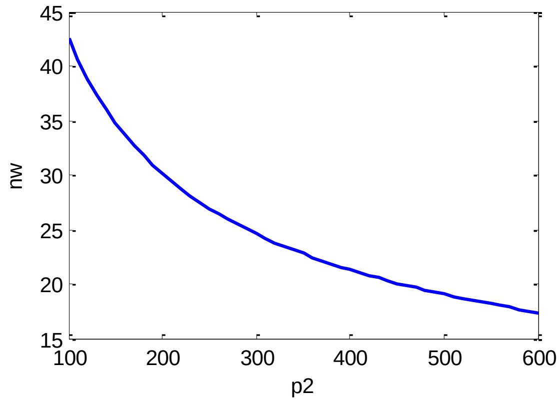

Fig.7

It can be seen that the required power gap between the fixed wing mode and the helicopter mode is large. The value of $\frac{P_h}{P_w}$ can reach 10, it is so big. As the engine has different fuel consumption and stability in different operating points, the engine and the aircraft matching unreasonably will lead to poor aircraft economy, engine working in a state of instability or dangerous situations. So we need a comprehensive design of the aircraft's fixed wing mode and helicopter mode combined with engine characteristics to make the power demand of the helicopter mode and fixed wing mode suit for the engine.

3 Aircraft and engine matching method

① Get the maximum available power , the minimum available power and the most economical power of the selected engine through experiment. When the engine is operating at the most economical power, it's fuel consumption is the lowest. Different type of engine has different the most economical power.

② Due to the special power demand of the canard rotary wing airplane: the power demand in the helicopter mode is large but the working time is short and the fixed wing mode requires less power but needs a long time to run in this mode, in the design of the aircraft we need to make the required power of helicopter mode equal to the maximum available power of the engine and make the required power of fixed wing mode equal to the most economical power. The relationship between the power loading of helicopter mode and the fixed wing mode is determined according to the above relationship.

③ According to the relationship between the helicopter mode and the fixed wing mode power loading, select the appropriate helicopter rotor disc loading, helicopter wingtip's speed and fixed wing wing-loading.

4 Apply this method to an 100kg level CRW airplane

Now we will design an 100kg level canard rotary wing airplane by this method. The cruising speed of the aircraft is required to be 160km/h.

4.1 Get the engine characters

I select a 2-stroke piston engine,this engine has small size, light weight and high power.
Performance characterization of the engine was performed. The engine was mated to an eddy current dynamometer to provide engine loading and torque/speed measurement[2]. The engine testing experimental setup and instrumentation are shown in Fig.8.

Fig.8

Here are the power-rotate speed curve(Fig.9), torque-rotate speed curve(Fig.10) ,specific fuel consumption (SFC)-rotate speed cure (Fig.11) and SFC-power cure(Fig.12) at different throttle valve for this engine.

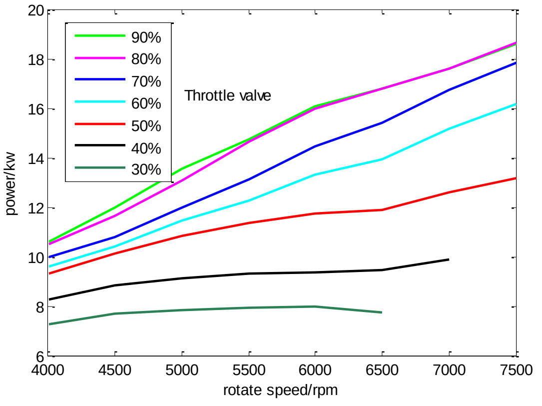

Fig.9

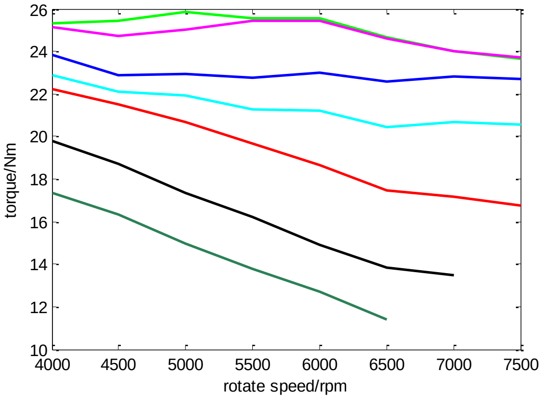

Fig.10

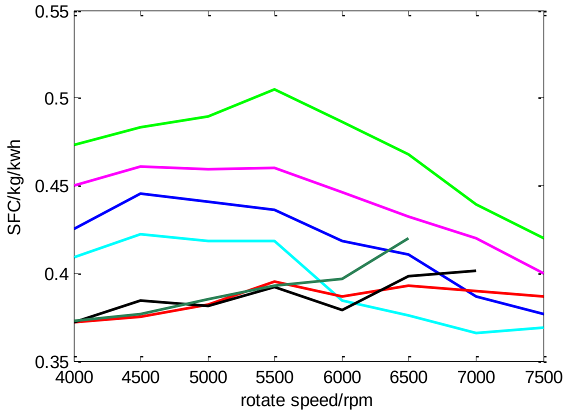

Fig.11

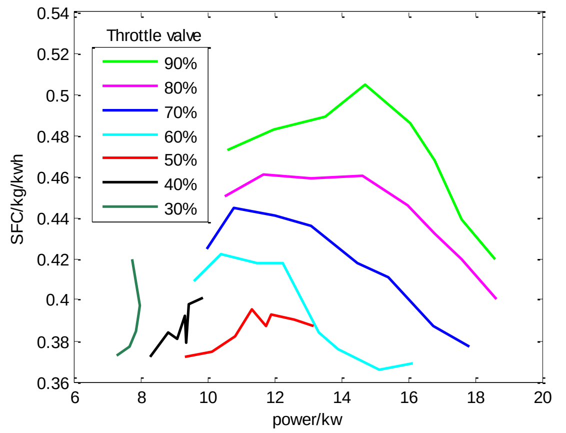

Fig.12

Next I will determine the operation point of the engine in fixed wing mode. These limits ensure that the engine can work stably for a long time:

- Firstly, engine should work in the torque drop segment in Fig.10[4].If the engine work in the torque rising segment, the engine will enter an unstable state. So the engine's rotate speed should be higher than 6000 rpm at 80% and 90% throttle valve.
- Secondly, engine working requires sufficient moment of inertia and we need the engine to output enough power at high throttle valve so the working speed of the engine can not be lower than 5000rpm.
- Thirdly, from Fig.12 we can see that the rate of SFC-power curve is very large at 30% and 40% throttle valve. At the same time, in order to ensure the stability of the engine when the aircraft is decelerating and lowering the altitude , operation point is not recommended at 30% -40% throttle valve.
- Fourthly, the engine rotates at high speed with low throttle valve will accelerate wear and reduce life expectancy, so the engine's rotate speed should be lower than 6500 rpm at 50% throttle valve.
- Fifthly, long hours of full-power engine working will accelerate wear and reduce life expectancy. Therefore, the engine power of fixed wing mode should be less than 75% of the maximum power.

According to the above restrictions, engine's available operation points of fixed wing mode is drawn in shaded section of Fig.13

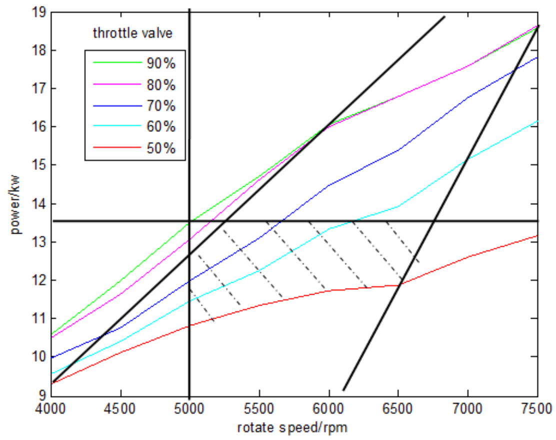

Fig.13

From Fig.13 we can get that the rang of engine power in fixed wing mode is from 11kw to 13.5kw.

According to Fig.12, SFC increases with the throttle valve increases and increases with power increases and then decreases.

To make the plane cruise economically, the engine working point in fixed wing mode is selected as follow:

Table.1

Parameters	Value
Sea level output power	11kw
Throttle valve	50%
Rotate speed	5000rpm

Because the plane flies at a height of 3000m in fixed wing mode.

Convert the engine's sea level parameters to 3000m height as follow[5]:

Table.2

Parameters	Value
3000m output power	7.57kw
Throttle valve	50%
Rotate speed	5000rpm

Because the helicopter mode vertical velocity is 2m/s, We assum that the power for helicopter mode vertical increasing is 1.5kw. Take 90% of the remaining power as the helicopter mode hovering power:

$$P_h = (18.5kw - 1.5kw)90\% = 15.3kw$$

Assuming that the propeller efficiency of fixed wing mode is 70%[6]. The cruising required power of fixed wing mode is :

$$P_w = 70\% \times 7.57kw = 5.299kw$$

So the ratio of required power of helicopter mode and fixed-wing mode is: $\frac{P_h}{P_w} = 2.89$ .We should design the aircraft based on this ratio.

4.2 Design the general paraments

From section 4.1 we come to: $\frac{P_h}{P_w} = 2.89$ .So the relationship between the power loading of the helicopter mode and the power loading of the fixed wing mode is $\frac{n_h}{n_w} = \frac{1}{2.89}$, the relationship between the $2.89n_h$ and p_1 and the relationship between n_w and p_2 are plotted on a same figure(Fig.14),as follows.

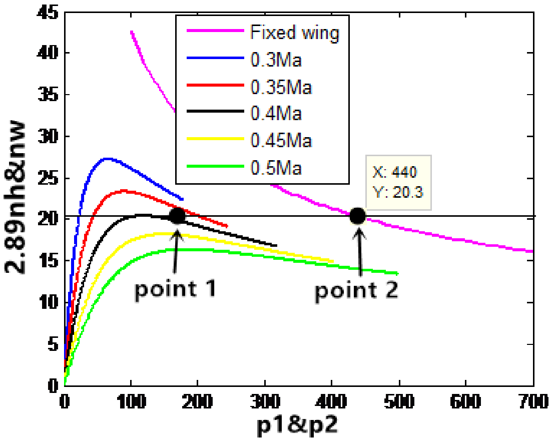

Fig.14

Draw any horizontal line($n_w = x$) on Fig.14, and intersect the curve. The parameters at the intersection points achieve the ratio of required power of helicopter mode and fixed-wing mode that we expect. Select the appropriate helicopter rotor disc loading, helicopter wingtip's speed and fixed wing wing-loading between the intersection points. If the aircraft parameters under the current value x do not meet the requirements, we can adjust the value of x until we find the intersection that satisfies the condition.

It can be seen from the figure that under the same value of x, the only fixed wing wing- loading can be determined, but the helicopter rotor disc loading and helicopter wingtip's speed have a variety of combinations, we need to combine the economy of the aircraft, the limit of the relationship of the rotor size and the wing size of the fixed wing, the helicopter rotor disc loading limit, the helicopter wingtip's speed limit and the hover efficiency to consider the value of these parameters. Because the helicopter mode is only the role of auxiliary take-off, we can sacrifice some flight performance under the premise of satisfying the maximum take-off weight.

From Fig.14 we can get that when p_2 is less than about 250, there is no point of intersection on the helicopter mode curve($2.89n_h$ - p_1). So the plane's cruising speed can not be lower than about 34m/s.

Because the cruising speed of the aircraft is required to be 160km/h, the fixed wing wing-loading should be 440 N/m^2 . I choose the following overall parameters. (point 1 and point 2 in Fig.14, x=20.3)

Table.3

Paramenters	Value
n_w	20.3
p_2	440 N/m^2
n_h	7.02
p_1	178.94 N/m^2
v	0.375 Ma
hover collective pitch	15°
hover efficiency	0.64
C_T	0.019

According to the above parameters other aircraft parameters can be calculated.

Weight : $m = n_w P_w = 108kg$

Total wing area: $S = \frac{G}{p_2} = \frac{mg}{p_2} = 2.39m^2$

Rotor disk area: $A = \frac{G}{p_1} = \frac{mg}{p_1} = 5.89m^2$

Rotor radius: $R = \sqrt{\frac{A}{\pi}} = 1.37m$

Fixed wing mode cruising speed:

$$V = \sqrt{\frac{2mg}{\rho S C_L}} = 44.7m/s$$

5 Conclusions

This article describes an aircraft and engine matching method of single-powered canard rotary wing (CRW) airplane. It is discovered that the ratio of helicopter mode required power and fixed wing mode required power must be within a reasonable range when the CRW airplane is powered by one engine and CRW airplane's lowest cruising speed is limited by engine characteristics. Making the required power of helicopter mode be equal to engine's maximize power and making the required power of fixed wing mode be equal to engine's economical power will be a good match. Single-powered reduces the dead weight , and the method described in this paper makes the single-powered VTOL more economical and stable.
Almost all VTOL aircraft can use this method to match the engine and general parameters

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