Propeller Control Strategy for Coaxial Compound Helicopters

Ye Yuan[1,2], Douglas Thomson[2] and Renliang Chen[1]

Abstract

The coaxial compound configuration has been proposed as a concept for future high-performance rotorcraft. The coaxial rotor system does not require an anti-torque device, and a propeller provides axial thrust. A well designed control strategy for the propeller is necessary to improve the performance and the flight dynamics characteristics. A flight dynamics model of coaxial compound helicopter is developed to analyze these influences. The performance and the flight dynamics characteristics in different propeller strategies were first investigated. The results show that there is an improvement in the performance in high-speed flight when the propeller provides more propulsive forces. It also illustrates that a reasonable allocation of the rotor and the propeller in providing thrust can further reduce the power consumption in the mid speed range. In other words, the propeller control strategy can be an effective method to improve the cruise-efficiency. The flight dynamics analysis in this paper includes trim and handling qualities. The trim results prove that the propeller strategy can affect the collective pitch, longitudinal cyclic pitch, and the pitch attitude. If the control strategy is designed only to decrease the required power, it will result in a discontinuity in the trim characteristics. Handling qualities are investigated based on the ADS-33E-PRF requirement. The result demonstrates that the bandwidth and phase delay results and eigenvalue results in various speed at different propeller strategies are all satisfied. However, some propeller control strategies lead to severe inter-axis coupling in high-speed flight. Based on these results, this paper proposes the propeller control strategy for the coaxial compound helicopter. This strategy ensures good trim characteristics and handling qualities which satisfy the related requirements, and improves the flight range or the performance in high-speed flight.

Keywords: Coaxial Compound Helicopter; Propeller Control Strategy; Trim Characteristics; Handling Qualities; ABC rotor; Inter-axis Coupling; Flight Dynamics

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Nomenclature

$\bar{e}$	=	non-dimensional flapping offset
p, q	=	angular velocities in body axes (*rad/s)*)
v	=	induce velocity (*kg/(m.s^2)*)
x, y, z	=	position coordinate (*m*)
K_{10}	=	equivalent flapping spring rigidity (*N.m/rad*)
L, M, N	=	the external forces about the body axes (*N.m*)
P	=	power required (*kW*)
R	=	rotor radius (*m*)
V_f	=	forward speed (*m*)
W_{tip}	=	tip flapping amplitude (*deg*)
$W'_{0.75R}$	=	flapping angle at 0.75R (*deg*)
X, Y, Z	=	the external moments about the body axes (*N*)
α, β	=	attack and sideslip angle (*deg*)
ρ	=	air density (*kg/m^3*)
$\bar{\omega}_n$	=	non-dimensional flapping frequency
Ω	=	rotor speed (*rad/s*)
Γ	=	control phase angle (*deg*)

Subscripts

u, l	=	upper and lower rotor
F	=	fuselage
HT	=	horizontal tail
P	=	propeller
R	=	rotor
VT	=	vertical tail

1. Introduction

The coaxial compound helicopter has gained a lot of research interest in recent years due to its high-speed performance [1~2] and significant cruise-efficiency [3]. The propeller is the key feature for the coaxial compound helicopter to achieve these two outstanding characteristics. Usually, the main rotor of a conventional helicopter is responsible for providing both the lifting and propulsive forces. However, the propeller of the coaxial compound helicopter can offload the rotor by producing propulsive forces, which improves the efficiency in high-speed flight by alleviating the compressibility effect across the advancing side of the rotor disc [4]. Meanwhile, it may also improve performance in the mid speed range, giving helicopter have a better cruise-efficiency and longer flight range compared with conventional helicopters [5].

The propeller gives the coaxial compound helicopter another control input - propeller collective pitch. The control strategy of the propeller collective pitch can be scheduled with the forward speed to minimize the power consumption [6]. Too high or too low propeller collective pitch would results in a nose-up or nose-down pitch attitude, producing extra fuselage parasite drag [7]. Also, in hover and low speed flight, the propeller should be feathered so that it provides no axial thrust [8]. Propeller control strategy would couple with the flight dynamics characteristics. Firstly, if the propeller begins to provide all needed thrust at a given speed point, it may lead to sudden changes in flight dynamics [9]. Secondly, because the propeller collective pitch would be mixed with the cyclic pitch in the longitudinal controller, its strategy would alter the control characteristics, and further modify the handling qualities [10]. Further, the coaxial compound helicopter uses an ABC (Advancing Blade Concept) rotor [11], which has the higher flapping rigidity to delay retreating blade stall in high-speed flight. The ABC rotor would alter the flight dynamics feature of the helicopter and so influence the control strategy of the propeller [12]. Therefore, the propeller control strategy of the coaxial compound helicopter should be designed carefully to ensure good performance and flight dynamics characteristics.

There has been extensive research to date on the aspects of propeller control strategy. Many types of research have been done to study the effect of the propeller on the performance, trim, and stability characteristics of the other types of compound helicopter [13~17]. The results show that an auxiliary propeller influences the flight dynamics characteristics and it can be utilized to reduce the power consumption in the mid speed range and high-speed flight. They all mainly focus on the conventional compound helicopter, such as X-3 helicopter and X-49A helicopter. The propellers of these helicopters are entirely different from that of the coaxial compound helicopter regarding its function and feature. The first matured coaxial compound helicopter was the XH-59A. It utilized an additional control input to control the thrust provided by the auxiliary propulsion, which naturally increases the workload of the pilot [18~19]. The X2 Technology Demonstrator (X2TD) coaxial compound helicopter makes progress by arranging a fixed pitch attitude schedule to decide the propeller collective pitch at different speeds [20~22]. This method is used to reduce the overall power consumption of the helicopter. According to all of the above, the design of the propeller control strategy is still under development, and little information is openly available.

In light of the preceding discussion, this article firstly presents a flight dynamics model of the coaxial compound helicopter, followed by the validation of trim results in helicopter and compound mode respectively. Then, the paper introduces the format of the propeller control strategy used in the research. The performance , the trim features, and the handling qualities in various propeller strategies are investigated. Lastly, this paper will develop a design method of the propeller control strategy with the consideration of both the flight dynamics and the performance characteristics.

2. Modelling and Validation

2.1. Modelling

In developing a coaxial compound helicopter model, the external forces and moments are composed of five parts: rotor, propeller, horizontal tail, vertical tail, and fuselage.

Rotor Model

The rotor model can be summarized as Fig.1.

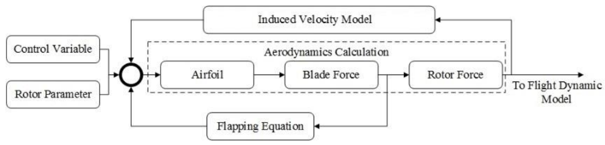


Fig 1 The ABC Rotor Aerodynamics Model

The induced velocity model in this paper is based on the Pitt-Peter dynamic inflow model [22]. The aerodynamics interference between rotors is simulated by following the method proposed by Ferguson [23]. It assumes the inflow of the lower rotor does not affect the upper rotor’s ability to generate thrust, and the rotors are sufficiently close together that the wake from the upper rotor does not fully develop. Therefore, the induced velocities of upper and lower rotor are Eq. (1) and Eq. (2):

$$v_u = v_u' \tag{1}$$

$$v_l = v_u' + v_l' \tag{2}$$

where v_u' and v_l' are the induced velocity calculated from the Pitt-Peters dynamic inflow model.

The motion of the blade includes the flapping motion and the lead-lag motion. In this article, only the flapping motion is taken into consideration. As the flapping rigidity of the ABC rotor is significantly higher than that of the conventional rotor, and the Coriolis force provided by the flapping motion is lower, which leads to the relatively small amplitude of the lead-lag motion.

Therefore, the presence of lead–lag motion contributes little to the overall flight dynamic characteristics of the coaxial compound helicopter.

The higher flapping rigidity of the ABC rotor also modifies the flight dynamics characteristics of the coaxial compound helicopter. To simulate the flapping motion more precisely, this paper utilizes the equivalent flapping offset and flapping spring method [24~25]. This equality method is shown in Fig.2.

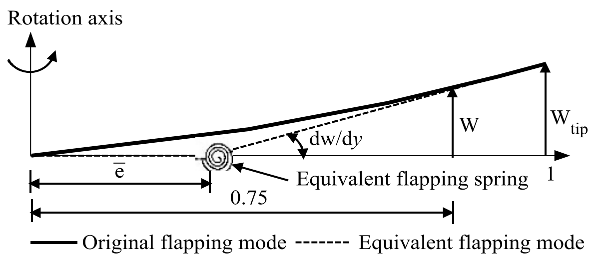


Fig 2 Rigid Blade's Flapping Equivalence

The non-dimensional flapping offset $\bar{e}$ can be obtained by:

$$\bar{e} = 1 - \frac{W_{tip}}{R \cdot W'_{0.75}} \tag{3}$$

The equivalent flapping offset is used to fit into the blade flapping mode. The rigidity of the equivalent flapping spring is obtained by Eq. (4) to guarantee the flapping frequency:

$$K_{10} = (\bar{\omega}_n^2 - 1 - \frac{\bar{e}RM_\beta}{I_\beta})I_\beta\Omega^2 \tag{4}$$

According to the equivalence method, the flapping motion equation is represented by the Eq. (5).

$$\ddot{\beta} + (1 + \bar{e}RM_\beta / I_\beta)\beta + K_{10}\beta / I_\beta\Omega^2 + M_A = 0 \tag{5}$$

where M_A contains the aerodynamic, Coriolis, inertia and gravity moments. β is the blade flapping angle.

The aerodynamic load calculation, including airfoil aerodynamics, blade force, and rotor force calculation parts, is similar to a conventional rotor aerodynamic load calculation model [25]. The airfoil section uses lifting line model based on the airfoil aerodynamics look-up table, and then by integrating the result, the aerodynamic loads can be obtained.

Propeller model

The propeller model is similar to the rotor model except that there is no flapping motion in the propeller. The blade element forces are integrated to give the total forces X_P, Y_P, Z_P and the aerodynamics moments $L_P, \mathrm{M}_P, \mathrm{N}_P$. Details of the propeller aerodynamic model are shown in Reference [23]. Therefore, the force is obtained, and the overall moment of the propeller can be represented by Eq. (6).

$$\begin{bmatrix} L_p \\ M_p \\ N_p \end{bmatrix} = \begin{bmatrix} L_p + \mathrm{Y}_p z_p - Z_p \mathrm{y}_p \\ M_p + \mathrm{Z}_p \mathrm{x}_p - X_p \mathrm{z}_p \\ N_p + \mathrm{X}_p \mathrm{y}_p - Y_p \mathrm{x}_p \end{bmatrix} \tag{6}$$

Horizontal tail & Vertical tail model

A simple 2-D representation of the horizontal and vertical tail using conventional strip theory is incorporated into the proposed model [26]. The lift coefficient and drag coefficient can be obtained from a 2-D airfoil aerodynamics look-up table. Therefore, the force and moment of horizontal tail and vertical tail can be represented in Eq. (7~10).

$$\begin{bmatrix} X_{ht} \\ Y_{ht} \\ Z_{ht} \end{bmatrix} = \begin{bmatrix} \cos\beta_{ht}\cos\alpha_{ht} & -\sin\beta_{ht}\cos\alpha_{ht} & -\sin\alpha_{ht} \\ \sin\beta_{ht} & \cos\beta_{ht} & 0 \\ \cos\beta_{ht}\sin\alpha_{ht} & -\sin\beta_{ht}\sin\alpha_{ht} & \cos\alpha_{ht} \end{bmatrix} \bullet \begin{bmatrix} -q_{ht}S_{ht}C_{D,ht} \\ 0 \\ -q_{ht}S_{ht}C_{L,ht} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} L_{ht} \\ M_{ht} \\ N_{ht} \end{bmatrix} = \begin{bmatrix} y_{ht}Z_{ht} - z_{ht}Y_{ht} \\ z_{ht}X_{ht} - x_{ht}Z_{ht} \\ x_{ht}Y_{ht} - y_{ht}X_{ht} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} X_{vt} \\ Y_{vt} \\ Z_{vt} \end{bmatrix} = \begin{bmatrix} \cos\beta_{vt}\cos\alpha_{vt} & -\sin\alpha_{vt} & -\sin\beta_{vt}\cos\alpha_{vt} \\ \cos\beta_{vt}\sin\alpha_{vt} & \cos\alpha_{vt} & -\sin\beta_{vt}\sin\alpha_{vt} \\ \sin\beta_{vt} & 0 & \cos\beta_{vt} \end{bmatrix} \bullet \begin{bmatrix} -q_{vt}S_{vt}C_{D,vt} \\ -q_{vt}S_{vt}C_{L,vt} \\ 0 \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} L_{vt} \\ M_{vt} \\ N_{vt} \end{bmatrix} = \begin{bmatrix} y_{vt}Z_{vt} - z_{vt}Y_{vt} \\ z_{vt}X_{vt} - x_{vt}Z_{vt} \\ x_{vt}Y_{vt} - y_{vt}X_{vt} \end{bmatrix} \quad (10)$$

where q is the dynamic pressure, which can be calculated with Eq. (11).

$$q = \frac{1}{2} rV^2 \quad (11)$$

In addition, in Eq. (7~10), S_{ht}, S_{vt} is the area of the horizontal tail and the vertical tail. C_D, C_L are drag and lift coefficient obtained from airfoil aerodynamics look-up table.

Fuselage model

The fuselage model is based on the wind tunnel test results. The force and moment provided by fuselage are obtained by Eq. (12~13).

$$\begin{bmatrix} X_F \\ Y_F \\ Z_F \end{bmatrix} = \begin{bmatrix} -q_F S_F C_{DF} \\ -q_F S_F C_{YF} \\ -q_F S_F C_{LF} \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} L_F \\ M_F \\ N_F \end{bmatrix} = \begin{bmatrix} q_F S_F l_F C_{RF} \\ q_F S_F l_F C_{MF} \\ q_F S_F l_F C_{NF} \end{bmatrix} \quad (13)$$

where S_F is the sectional area of the fuselage; l_F is the fuselage length; $C_{DF}, C_{YF}, C_{RF}, C_{LF}, C_{MF}, C_{NF}$ are the drag force, lateral force, lift force, rolling moment, pitching moment and heading moment coefficients, which are dependent on the fuselage angle of attack and angle of sideslip.[27]

2.2. Validation

The model is verified by comparing trim results with flight test data with the XH-59A [18]. In the compound mode, flight simulation data found in reference [23] is used because of the lack of other experiment data. The primary data for the XH-59A helicopter is shown in Table.1.

Table 1 XH-59A Helicopter Parameters

Parameter	Value
Rotor radius/m	5.49
Number of blades	3×2
Pre-twist/(°)	-10
Rotor speed/(rad/s)	35.9 (Helicopter mode)
Taper ratio	0.5
Flapping frequency/Ω	1.4
Shaft spacing/m	0.77
Horizontal tail area/m^2	5.57
Vertical tail area/m^2	2.79
Takeoff weight/kg	5500
Lower Rotor position/m	(0.00,0.00,-0.89)
Centre of gravity/m	(0.00,0.00,0.00)
Horizontal tail position/m	(-6.80,0.00,0.20)

Vertical tail position/m	(-6.80,0.00,-0.50)

As the XH-59A helicopter uses auxiliary propulsion rather than a propeller to provide the thrust, this paper utilizes propeller data from reference [23]. The propeller design parameters are in Table.2.

Table 2 Parameters of Compound Propeller

Parameter	Value
Propeller radius/m	1.3
Propeller Rotor speed/(rad/s)	162
Negative Pre-twist/°	-30
Solidity	0.2
Position/m	(-7.66,0.00,0.00)

There are three additional differences between the coaxial compound helicopter and the conventional helicopters in the trim process, which are the propeller control strategy, the rotor speed, and the lift-offset trim.

For the compound mode, the trim algorithm has an additional unknown trim variable, the propeller collective. In the validation process, the fixed pitch attitude schedule from reference [23] is used to trim the propeller.

Compressibility effects at the advancing blade tip can be an issue in high-speed flight resulting in a significant increase in drag [28~29]. The aim of slowing down the rotor speed is to keep it away from compressibility impacts at the advancing blade tip during high-speed flight. The rotor speed changes following the Eq. (14) in compound mode [23]. In helicopter mode, it is constant.

$$\Omega = \begin{cases} 35.9, V_f < 70\text{m/s} \\ 35.9 - \dfrac{3.59(V_f\text{-}70)}{30}, \quad V_f \geq 70\text{m/s} \end{cases} \tag{14}$$

where V_f is the forward flight speed.

The Lift-offset (LOS) of the ABC rotor has a marked impact on its efficiency [30~32]. A coaxial rotor with the LOS can attain good efficiency in high-speed flight range by operating with more lift on the advancing side than on the retreating side of the rotor disc. The LOS can be regulated by lateral cyclic pitch differential $\theta_{1c,d}$ or rotor control phase angle Γ. Flight tests in helicopter mode used the rotor control phase angle Γ to control the LOS. Thus, in the validation process. This article utilizes Eq.(15) to make the control phase angle in accordance with the flight test [18], which is utilized in the validation of the helicopter mode. Also, the velocity range of different control phase angle is labelled in the figure.

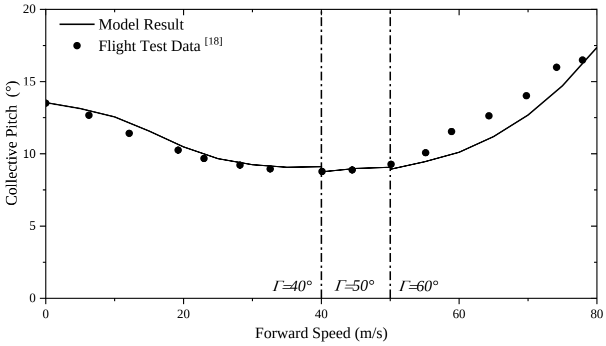
$$\Gamma = \begin{cases} 40^\circ, V_f < 40\text{m/s} \\ 50^\circ, 40\text{m/s} \leq V_f \leq 50\text{m/s} \\ 60^\circ, V_f > 50\text{m/s} \end{cases} \tag{15}$$

As for the compound mode, the lateral cyclic pitch differential $\theta_{1c,d}$ is used according to the reference [23]. It is set to be a trim variable to trim the LOS. The LOS is given as Eq. (16).

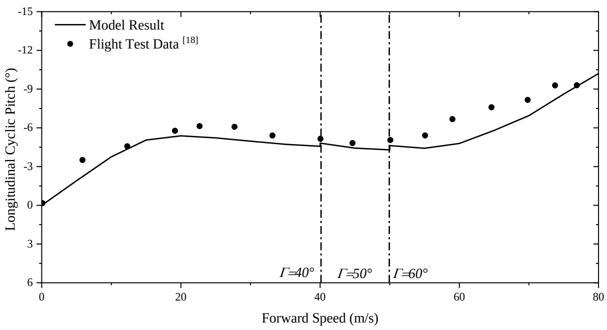
$$LOS = 0.00002V_f^2 \tag{16}$$

The lateral cyclic pitch differential trim result with respect with LOS set in compound mode is shown below in Fig.4.

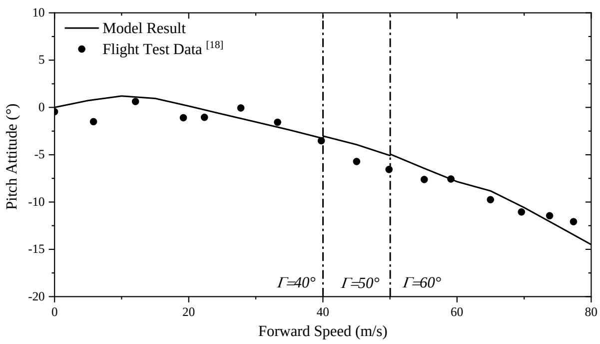
The trim results calculated by the flight dynamics model proposed by this paper for helicopter and compound mode are shown in Fig.3 and Fig.4.



(a) Collective Pitch - Helicopter Mode

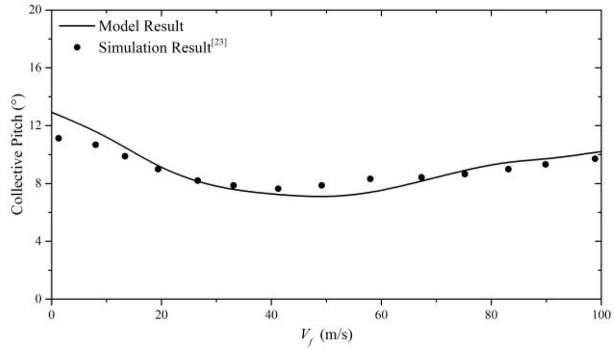


(b) Longitudinal Cyclic Pitch - Helicopter Mode

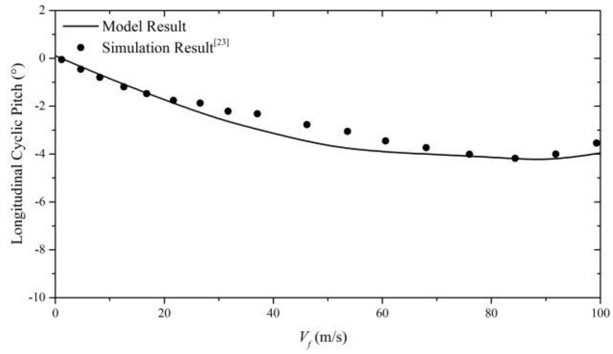


(c) Pitch Attitude - Helicopter Mode

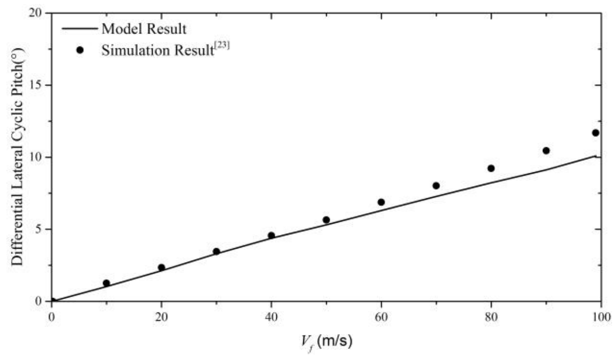
Fig 3 Trim Validation in Helicopter Mode



(a) Collective Pitch - Compound Mode



(b) Longitudinal Cyclic Pitch - Compound Mode



(c) Differential Lateral Cyclic Pitch - Compound Mode

Fig 4 Trim Validation in Compound Mode

As demonstrated in Fig. 3 and Fig. 4, the results obtained by this model coincide well with the flight test data and the simulation result from other article. This gives confidence that proposed model can be used to analyze the effect of different propeller control strategy on the flight dynamics characteristics and performances.

3. The influence of propeller control strategy

The rotor and propeller are the only two ways to provide the propulsive forces. In this article, the factor *a* in Eq. (17) is utilized to decide the thrust allocation between rotors and propeller:

$$X_P / (X_R + X_P) = a \tag{17}$$

where X_P is the axial thrust provided by the propeller; X_R is the thrust provided by coaxial rotors. Usually, the value of a should be above 0, and may be above 1.0. This implies that the rotor disc flapped aft so that the X_R is negative. It is noticeable that the factor a could also represent the allocation of the longitudinal controller between rotor and propeller. As shown in Eq. (18).

$$\Delta\theta_{I,\ l} = a \cdot \Delta\theta_{C,p} + (1-a)\Delta\theta_{1s} \tag{18}$$

where $\Delta\theta_{I,\ l}$ is the control input increment in longitudinal; $\Delta\theta_{C,p}$ is the propeller collective increment; $\Delta\theta_{1s}$ is the increment of the longitudinal cyclic pitch. When $a=0$, it means that the longitudinal controller would directly link to the longitudinal cyclic pitch. The influence of propeller control strategy(i.e. different values of a) on performance, trim, and handling qualities characteristics will be analyzed.

It should be mentioned that the extra trim variable settings (including LOS and rotor speed) in the analysis part below are the same with the compound mode in the validation process to show clearly the effect of the propeller control strategy on the performance and the flight dynamics characteristics.

3.1 Performance Analysis

The power required for various values of a with speed is shown in Fig. 5. The power required in helicopter mode is also added in this figure as a comparison.

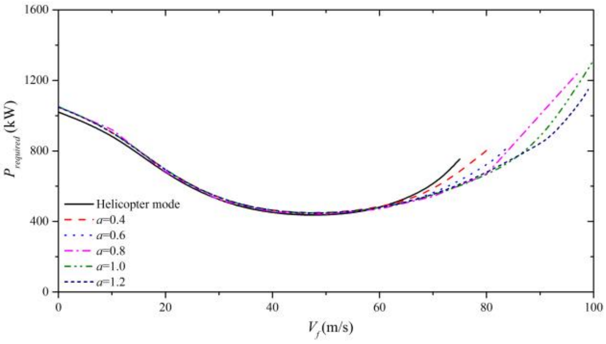


Fig 5 Power Required at Different a

In hover, the required power in the helicopter mode is lower due to the extra propeller power in compound mode. In high-speed flight, the power consumption of helicopter mode is higher than the compound mode because of the lower efficiency of the coaxial rotor in providing propulsive forces. When the forward speed is above 80m/s, the helicopter cannot trim because of the rotors limitation in providing thrust.

The performance advantage of the compound propeller would begin to show up with speed increasing. According to the numerical results with various a, at the forward speed of 47m/s, the required power with $a=0.8$ becomes less than that of helicopter mode. The power consumption of the propeller contains the induced power and the profile power. The induced power is decided by the propeller thrust and the profile power has rarely relationship with the thrust. In low speed forward flight, the induced power is small, but the profile power could still increase the overall power consumption of the helicopter. Thus, the propeller should be feathered at this flight range. When the speed is high enough, the propeller begins to show its advantage in reducing the overall power consumption.

With the speed increases, the a value at which power consumption is minimum also grows. Also, the effect of a on the performance is more significant in high-speed flight. In addition, the helicopter cannot trim in high-speed flight when the factor a is relatively small. This is because the compound propeller cannot provide enough thrust for the helicopter, leading to extra thrust being required from the rotors, which may be above its capability.

It is remarkable from Fig. 5 that, with different propeller control strategies, the compound mode could not only improve the performance in high-speed flight but also increase the flight range of the helicopter. The flight range can be appropriately measured by the parameter of $max(V_f \ / \ P_{required})$ [33]. Fig. 5 shows that in compound mode, this parameter is higher than that of helicopter mode. It means that the propeller control strategy can be a potential method to improve the flight range.

3.2 Trim Analysis

Fig. 6 to Fig. 8 shows trim results at different speed with various a, which includes the collective pitch, the pitch attitude, and the longitudinal cyclic pitch. The trim results in helicopter mode is also added as a comparison.

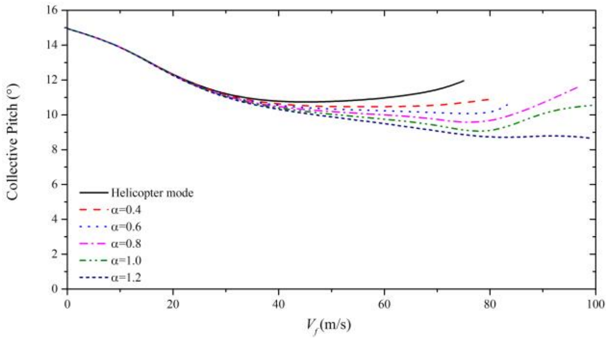


Fig 6 Collective Pitch Trim Result at Different a

Fig 6 shows that the increase of collective pitch with forward speed experienced by the conventional helicopter is much less with the compound. The change in collective pitch reduces further as the value of a is increased. In other words, it reveals how much the rotor can be offloaded by the propeller. This phenomenon can be reflected by the pitch attitude trim results in Fig. 7.

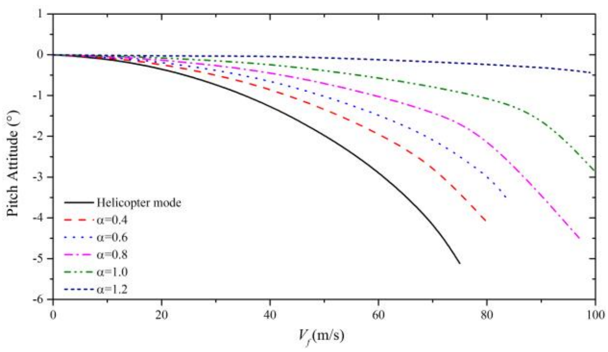


Fig 7 Pitch Attitude Trim Result at Different a

The propeller control strategy factor a has a dramatic influence on the trim result of pitch attitude, as shown in Fig. 7. The increasing of factor a leads to extra nose up pitch attitude. The thrust produced by the rotor reduces as the factor a increases, which indicates less forward-tilt of the rotor disc. On the other hand, as the rigidity of ABC rotor is relatively high, the forward-tilt of the rotor disc drives the pitch attitude to nose-up. Also, the alteration of pitch attitude also makes a difference of the longitudinal controller result. The longitudinal cyclic pitch trim result is shown in Fig. 8.

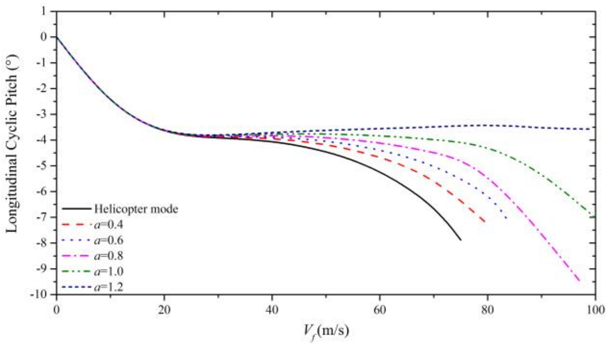


Fig 8 Longitudinal Cyclic Pitch Result at Different a

As demonstrated in Fig .8, the propeller control strategy factor a further decreases the longitudinal cyclic pitch. Increasing the factor implies less thrust given by the rotor, which also means less longitudinal cyclic pitch is needed in trim.

According to Fig. (6~8), the factor a has a strong influence on the trim characteristics. If the propeller control strategy is only designed to reduce the power consumption, the trim results are shown in Fig.9.

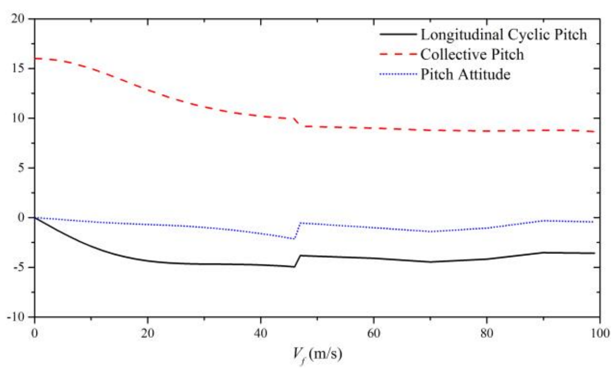


Fig 9 Trim Results with Propeller Only for Reducing Power

This control strategy is obviously unacceptable due to the severe fluctuations in trim characteristics. The discontinuity is due to the propeller obviously delivers significant thrust right from the start (47m/s). Therefore, the design of propeller control strategy should also consider the trim characteristics to prevent these fluctuations, because the fluctuations would lead to unsatisfied riding qualities, which is important in handling qualities.

3.3 Handling Qualities Analysis

The handling qualities analysis in this paper includes the short-term response (Bandwidth and Phase Delay), the mid-term response to control inputs (eigenvalues), and the inter-axis coupling.

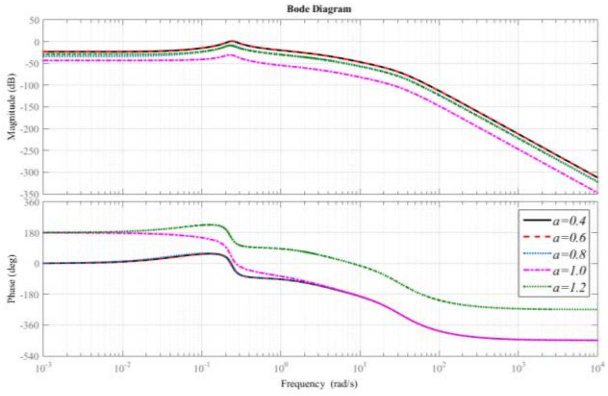
Bandwidth & Phase Delay

To obtain the bandwidth and phase delay in longitudinal channel, the dynamic models of the control mechanism and the actuator are needed, this paper utilizes a standard transfer function of Eq. (19) and Eq. (20) to simulate them [34].

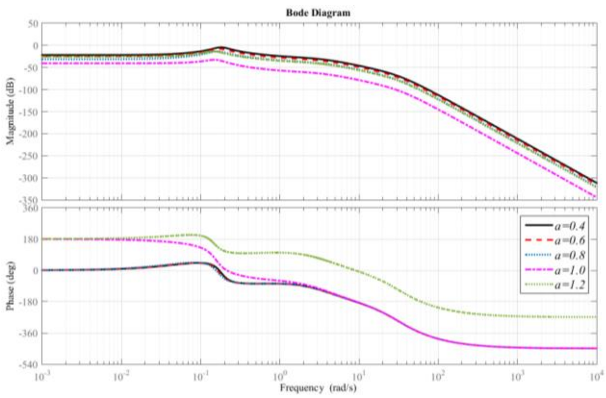
$$S_{Control} = \frac{16.9747}{s^2 + 44.4s + 986} \tag{19}$$

$$S_{Actuator} = \frac{1}{0.02s + 1} \tag{20}$$

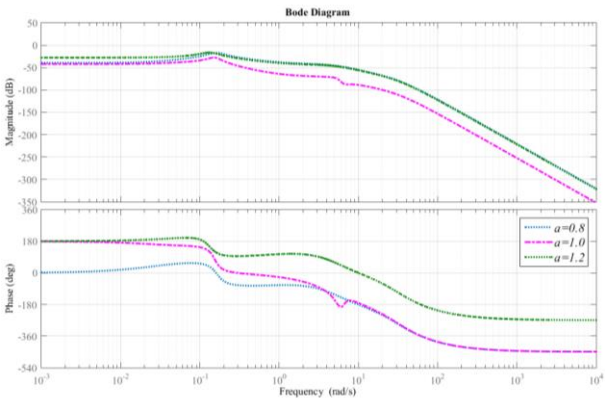
where $S_{Control}$ is the dynamic model of the control mechanism; $S_{Actuator}$ is the dynamic model of the actuator. Thus, the bode diagrams of different factor a at various speed are shown in Fig.10.



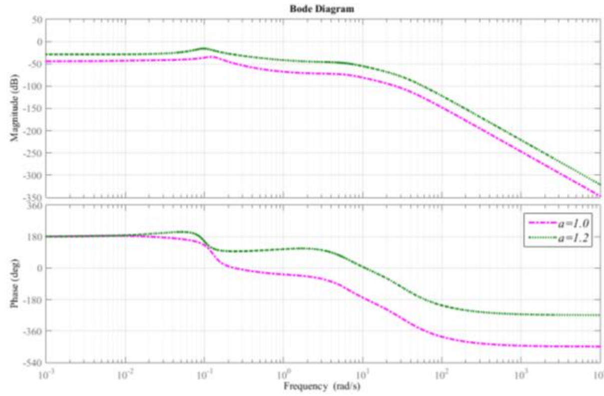
(a) V_f=40m/s



(b) V_f=60m/s



(c) V_f=80m/s



(d) V_f=100m/s

Fig 10 Bode Diagram of Longitudinal Channel

According to Fig.10, the bandwidth and the phase delay results at different a are shown in Table.3.

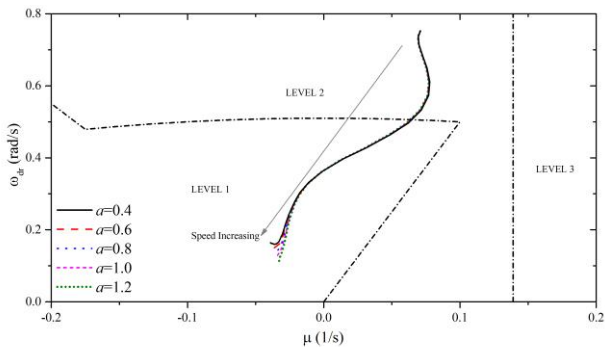
Table 3 The bandwidth and phase delay at different a

Bandwidth/ Phase delay	a=0.4	a=0.6	a=0.8	a=1.0	a=1.2
V_f=40m/s	3.76/ 0.051	3.76/ 0.051	3.77/ 0.051	3.79/ 0.052	37.9/ 0.009
V_f=60m/s	4.87/ 0.052	4.87/ 0.052	4.87/ 0.052	4.87/ 0.052	38.1/ 0.006
V_f=80m/s	-	-	5.73/ 0.052	5.43/ 0.052	38.6/ 0.006
V_f=100m/s	-	-	-	7.26/ 0.054	38.7/ 0.006

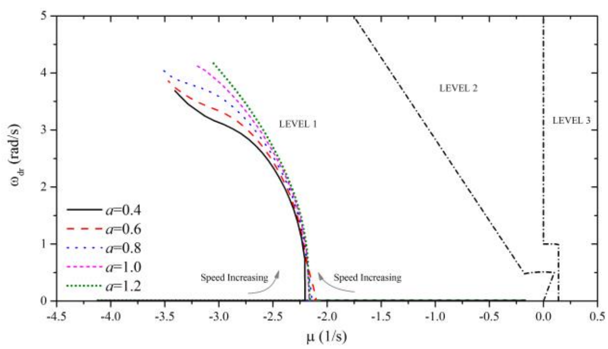
Fig. 10 and Table 3 indicate that the bandwidth and phase delay are all in Level 1 at various a according to the ADS-33E-PRF [35] requirement. This specification has been widely used in helicopter handling qualities assessment and related control strategy design [36]. Also, it is worth noting that when factor a is equal to 1.2, the bandwidth and the phase delay have dramatically changed. As demonstrated in Eq. (18), when $a=1.2$, the positive longitudinal controller increment leads to negative longitudinal cyclic pitch, which would result in the change of the coupling relationship in longitudinal channel. This change could influence the short-term characteristics, especially, the bandwidth and phase delay to a large extent.

Eigenvalues

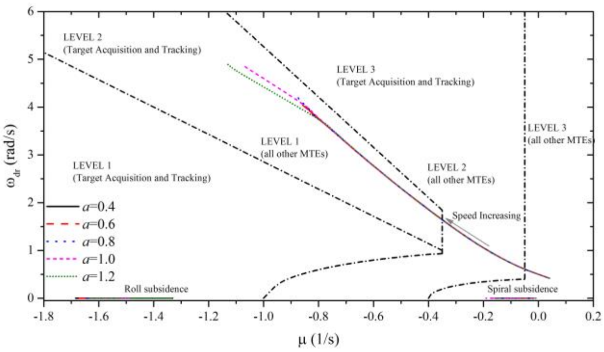
The eigenvalues of the coaxial compound helicopter at different a were been calculated. The result is shown in Fig.11 plotted with respect to the boundaries from the ADS-33E-PRF requirement.



(a) The Phugoid Mode



(b) The Short Period Pitch Mode



(c) The Lateral-Heading Oscillation Results

Fig 11 Eigenvalue Results at different a

As demonstrated in Fig.11 (a), the phugoid pitch mode is in Level 2 in low-speed flight because the ABC rotor provides negative incidence stability [37] and the dynamic pressure is too small to make the horizontal tail effective in providing incidence stability. In Fig.11 (b), the short period pitch satisfies Level 1 based on the ADS-33E-PRF requirement for all a. In addition, the propeller control strategy factor a only influences the longitudinal stability result in high speed. It alters the trim pitch attitude, which would modify the inflow of rotor and tails, and further change the stability derivative of the helicopter.

The lateral and heading stability eigenvalues are shown in Fig. 11(c). The Dutch roll mode stability is lower in hover and low-speed flight and improved with increasing speed. The coaxial compound helicopter only has the vertical tail to provide the lateral stability, which has low efficiency when the forward speed is relatively small. In high-speed flight, the stability of the Dutch roll mode is improved as the dynamic pressure at vertical tail rises so that it can provide more lateral stability, which is the unique feature of the coaxial helicopter [38]. The propeller control strategy factor a influences the stability of Dutch roll mode in high speed due to its torque providing extra roll moment to the helicopter. The spiral subsidence mode and the roll subsidence mode are all in Level 1, and it has no significant relationship with the factor a according to the Fig. 11(c).

Coupling

The inter-axis coupling of the roll to pitch and the pitch to roll can be studied by calculating average q/p and p/q (dB). The results are shown in Fig.12 with respect to the requirement of ADS-33E-PRF.

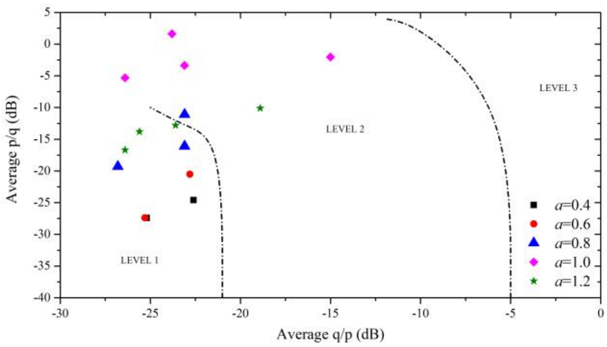


Fig 12 The Average q/p and p/q at Different a

The propeller control strategy factor a hardly affects the q/p coupling in most cases, as various propeller control strategies have no direct connection to the lateral control. However, the factor a influences the inter-axis coupling of p/q, as shown in Fig. 12. When the factor a is relatively small, the rotor provides a pitching moment that is much larger than the roll moment given by the propeller (the torque of the propeller). It leads to relatively weak coupling, satisfying the requirement for Level 1. However, when the factor a is around 1.0, the coupling becomes much stronger, especially at high speed. The rotor provides little pitching moment. The roll moment provided by the torque of the propeller is relatively high. It makes the inter-axis coupling deteriorate to Level 2. Therefore, the propeller control strategy factor a should not be around 1.0 in high-speed flight.

4. Propeller Control strategy Design

4.1 Requirements

According to the analysis above, the propeller control strategy factor a influences the performance, the trim characteristics, and the handling qualities. These following advantages can be obtained by careful propeller control strategy design:

1) The power consumption in high-speed flight can be reduced.
2) The flight range of helicopter can be increased due to lower required power and therefore fuel consumption.

On the other hand, a poorly designed strategy leads to severe problems as follows:

1) The sudden start-up of propeller would result in the discontinuity in trim characteristics because of the sudden input of the propeller thrust, according to Fig.9.
2) The propeller control strategy would deteriorate the inter-axis coupling the roll to pitch when the control strategy factor a is around 1.0 in high-speed

flight.

Therefore, the requirement of the propeller control strategy has been concluded through the flight dynamics investigation above.

4.2 Control Strategy

Therefore, this paper utilizes the factor a in Eq. (17~18) to design the control strategy of the propeller in the coaxial compound helicopter. The objective function is shown in Eq. (21).

$$M_{ob,1} = P_{a,v_f=100m/s}, \; or, \; P_{a,v_f=70m/s} \tag{21}$$

where $M_{ob,1}$ is the key target point. This objective function sets the 100m/s and 70 m/s as key target speed points. The point of 100 m/s is related to the performance in high speed. The reference point of 70 m/s is used to improve the flight range of the helicopter, as shown to Fig. 5, the optimized speed of the coaxial compound helicopter in compound mode is around 70m/s.

The boundary condition in propeller control strategy can be divided into two parts based on the analysis above: the boundary condition of the trim result and the boundary condition of handling qualities. The boundary condition of the trim result is used to prevent severe discontinuity when propeller starts to provide thrust. The values of these boundary conditions are selected by the trim characteristics of this helicopter to make sure that the change during the propeller starts to work is no more aggressive than that in helicopter mode. The boundary conditions can be written in Eq. (22):

$$\begin{aligned}
&\left|\frac{d\theta_{0,trim}}{dV_f}\right| \le 0.01(rad \cdot s)/m \\
&\left|\frac{d\theta_{1c,trim}}{dV_f}\right| \le 0.01(rad \cdot s)/m \\
&\left|\frac{d\theta_{1s,trim}}{dV_f}\right| \le 0.01(rad \cdot s)/m \\
&\left|\frac{d\theta_{d0,trim}}{dV_f}\right| \le 0.01(rad \cdot s)/m \\
&\left|\frac{d\theta_{trim}}{dV_f}\right| \le 0.005(rad \cdot s)/m \\
&\left|\frac{d\phi_{trim}}{dV_f}\right| \le 0.005(rad \cdot s)/m
\end{aligned} \tag{22}$$

where $\theta_{0,trim}$ is the trim collective pitch; $\theta_{1c,trim}$ is the lateral cyclic pitch; $\theta_{1s,trim}$ is the longitudinal cyclic pitch; $\theta_{d0,trim}$ is the collective differential; θ_{trim} is the pitch attitude; the ϕ_{trim} is the roll attitude. This boundary condition guarantees that trim changes smoothly with the forward speed.

The propeller control strategy for the coaxial compound helicopter influences the handling qualities due to the inter-axis coupling. Thus, the boundary condition of handling qualities is shown in Eq. (23).

$$\begin{aligned}
&\frac{p}{q} \le -5dB \\
&\frac{q}{p} \le -10dB
\end{aligned} \tag{23}$$

With the analysis above, the flow chart of propeller control strategy design is shown in Fig. 13.

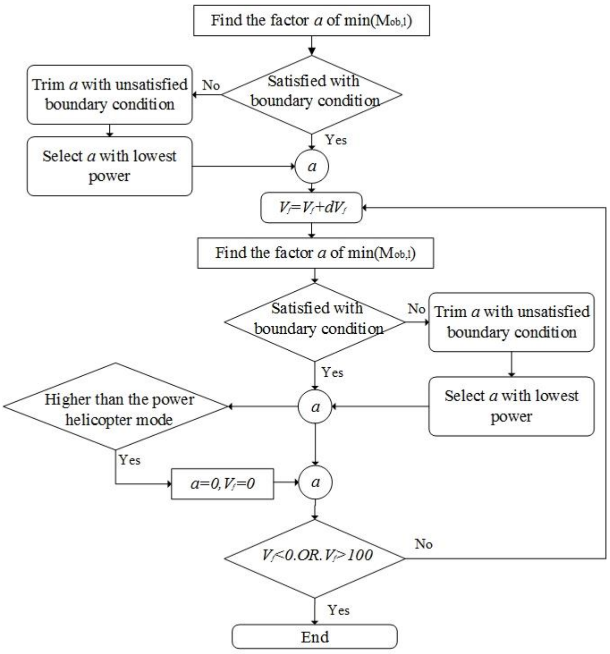
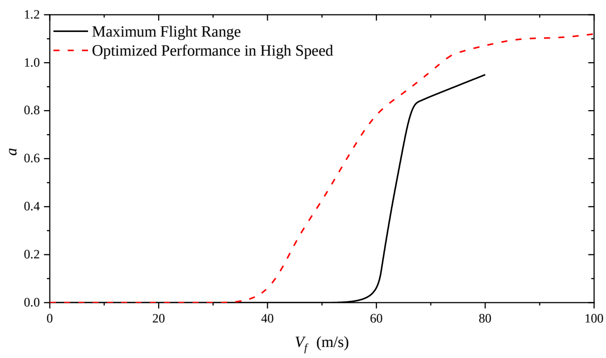


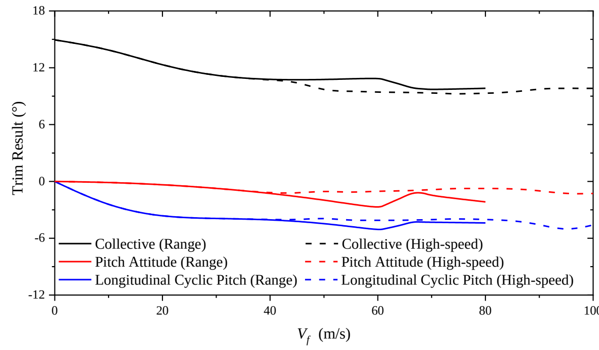
Fig 13 The flow chart of propeller control strategy design

4.3 Results and Discussion

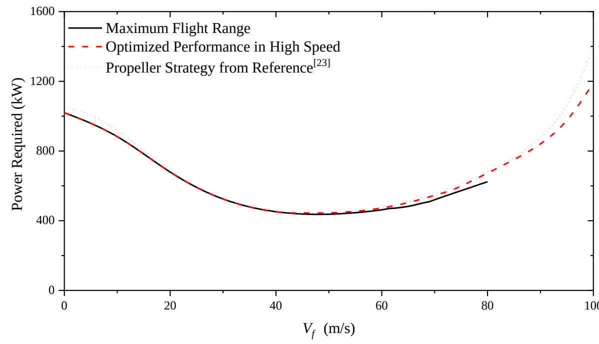
With this method, the propeller control strategy for increasing the flight range and for improving the performance in high speed was calculated. The result of the propeller control strategy and flight dynamics are shown in Fig. 14. The power required according to the propeller control strategy proposed in reference [23] is also shown in Fig.14 as a comparison.



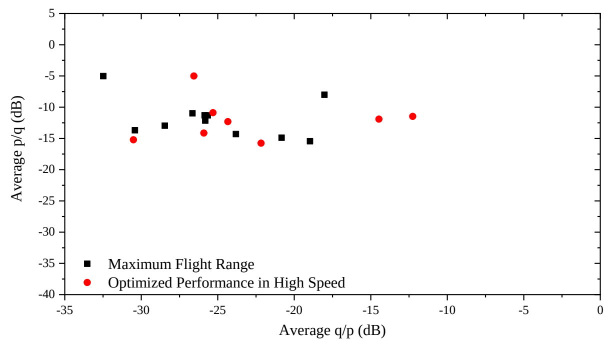
(a) Propeller control strategy factor



(b) Trim results



(c) Power required



(d) The average q/p and p/q

Fig 14 Propeller Control Strategy and Related Results

The following conclusions can be drawn from Fig.14.

1. The propeller control strategy proposed by this paper can be utilized to increase the maximum flight range or improve the performance in high-speed flight. Also, it guarantees the trim characteristics and handling qualities satisfy the given requirement.
2. As for the aim of the flight range improvement, the

boundary conditions of trim features take effect at the speed range of 60m/s to 70m/s, which leads the trim results to change slightly along with the forward speed, as indicated in Fig.14 (b). In addition, due to the inter-axis coupling, the strategy for cruise-efficiency cannot reach the required speed of 85m/s

3. As for the propeller control strategy for the performance in high-speed flight, the factor a has to remain above 1.0 at high-speed because of the boundary condition of inter-axis coupling and would be able to fall until the forward speed is relatively small.

5. Conclusions

The flight dynamics model described in this article was developed to investigate the influence of the propeller control strategy on the flight dynamics characteristics of the coaxial compound helicopter. The validity of the flight dynamics model was confirmed using the trim result in both helicopter and compound mode. The results from the simulation allow the following conclusions to be drawn.

1. The propeller control strategy influences the performance of the coaxial compound helicopter. It can be utilized to not only improve the performance in high-speed flight but also increase the flight range.
2. The propeller control strategy also influences the trim characteristics. The collective pitch, pitch attitude, and longitudinal cyclic pitch dramatically alter with various propeller control strategies. If the strategy is only designed to reduce the power loss, it brings about a discontinuity in trim, because of the sudden increase of the propeller thrust.
3. The bandwidth and phase delay and the eigenvalue requirements are satisfied with different propeller control strategies. However, the inter-axis coupling is significantly affected by the propeller control strategy in high-speed flight.
4. A propeller control strategy for the coaxial compound helicopter was developed to increase the flight range, or improve the cruise-efficiency. Also, the propeller control strategy can guarantee the trim characteristics and the handling qualities satisfy the given requirement.

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