ANALYSIS OF XH-59A ROTOR IN FORWARD FIGHT WITH HIGH EFFICIENCY TRIM METHOD

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Abstract

The control and performance of XH-59A rigid rotor helicopter were investigated using high efficiency trim method based on blade element method (BET) and gradient optimization method. The accuracy of BET was validated by coaxial rotor performance prediction in wind tunnel test. The trim model was developed with 7 control variables and 6-7 constrains. The variation of shaft angle, collective pitch and cyclic pitch of the upper and lower rotor with advancing ratio were investigated. Trimmed results were compared with flight test data in advancing ratio 0.07~0.4.

Nomenclature

A_1	Longitudinal cyclic blade pitch
B_1	Lateral cyclic blade pitch
C_{LR}/σ	Rotor lift coefficient
C_{XR}/σ	Net force coefficient on wind direction of the rotor
C_{YR}/σ	Rotor side force coefficient
C_{MZ}/σ	Helicopter yawing moment coefficient
C_{MY}/σ	Helicopter pitching moment coefficient
C_{MX}/σ	Helicopter rolling moment coefficient
C_{PR}	Rotor power coefficient
C_{PRC}	Correctional rotor power coefficient
D	Drag of the helicopter
L	Lift of the helicopter
LO	Lift offset
K	The empirical constant of inclination angle of rotor wake
P	Power of the rotor
V	Forward flight speed
v	Inherent induced velocity
v_i	Induced velocity
α	Shaft angle
θ	Rotor blade collective pitch
μ	Advance ratio
λ	Inflow factor
σ	Rotor solidity
δ	The flow interaction factor
χ	Wake inclination angle
Ψ	Azimuthal position of rotor blade

Subscripts

u	Upper rotor
l	Lower rotor

1 Introduction

The Advancing Blade Concept (ABC), first applied in XH-59A helicopter in 1973, employs a rigid coaxial rotor to balance the aerodynamic force and moment in rotor. It shows a potential advantage in high speed helicopter. However, the rigid coaxial rotor results in a strong flow interaction between each rotor, creating enormous challenges to aerodynamic analysis. With decades of development in helicopter aerodynamic and CFD, the ABC rotor regains attention in recent years.

The research of rigid coaxial rotor aerodynamic performance were carried out by wind tunnel experiment [1-3] and numerical method [4-7] separately. Performance and flow mechanism of coaxial rotor was presented in literatures [8-11]. Most of the studies confirm that the ABC rotor or the lift offset rotor has a better performance than traditional rotor. The wind tunnel experiment of full scale XH-59A helicopter was carried out without trim approach in 1981[2]. Unfortunately, in the rotor performance measurement, the shaft angle of attack are either positive or zero, which is different with the negative angle of attack in real flight situation. Therefore, the experiment is invaluable to this paper. Forward flight test data of XH-59A can be found in literature [8], rotor power and aircraft lift to drag ratio were plotted with flight speed. However, the detailed parameter of the coaxial rotors under various working conditions are not provided. The previous research of rotor performance are restricted in given states based on experience in the studies. To understand more states, a combination of control variables to match the real flight state trim requirement is necessary.

The strong nonlinear interaction of the ABC rotor makes it is hard to determine the control variables of the helicopter. In the hover state, it is essential to adjust the collective pitch of the upper and the lower rotor to balance both the weight of helicopter and the torque of each rotor. In the steady forward flight, all the forces and moments of the helicopter need to be trimmed, which makes 6 restrains. Nevertheless, the complicated control character of coaxial helicopter makes the problem even difficult, i.e. the direction control, collective pitch control, longitudinal control and transverse control are coupled together. Therefore, a cautious reliable and efficiency trim method is indispensable to adjust all the control input to a trim state.

The key problem of trim method contains the aerodynamic model of coaxial rotor and the numerical method for performance prediction. The ordinary aerodynamic models employed in trim model include Blade Element Method (BEM) [12], Free Wake Method (FWM) [3, 13], Vorticity Transport Model (VTM) [14] and Computational Fluid Dynamics (CFD) method [12]. The time cost of those models grow rapidly over its accuracy. An estimate of one trim state time cost in a desktop with CPU of i3 and RAM of 8G is about a week for CFD method, and half hour for BEM. A popular way to solve the trim problem is iterating solve the Jacobi matrix of the model. It is a feasible method in mathematics, but the result of the Jacobi matrix is occasionally far away from the effective range, which may be caused by the ill matrix. Besides, the number of control variables has to be equal to the number of the trim variables.

Lyu and Xu [13] used a free wake code combined a Jacobi matrix trim method to study the approximate model of X2 helicopter. The number of control variables and the number of the trim variables all are five. Shaft angle of attack is not considered as a control variable. The two cyclic pitch of the upper rotor were fixed and the side force of helicopter is not trimmed. After 50 iterations, the trim variables were converged. It was found that one working condition can be corresponding to eight trim states.

M et al. [12] developed a non-iterative trim progress using CFD method combined with a Jacobi matrix to deal with single rotor helicopter in forward flight. The controlled variables are collective and cyclic pitch, the trimmed variables are thrust coefficient, pitch and roll moment coefficients. To obtain the 3 control variables, four CFD simulation cases are necessary. If this method can be applied to coaxial rotor, the time cost is excessive due to the added variables. To understand the real performance of the rigid coaxial rotor, such as XH-59A, the control variables including shaft angle of attack are developed. In this paper, the iterative trim process are carried out based on BET method combined with gradient optimization method. The calculated performance are compared with flight test data of the real helicopter.

2 Trim Method for Forward Flight

2.1 Blade Element Theory

Blade element theory is basically the application of the standard process of airfoil theory to the rotating blade. To apply it to the coaxial rotor, a static inhomogeneous inflow model derived from Pitt-Peters dynamic inflow model [15] was used to represent the interaction between upper and lower rotor.

$$v_{iu} = (v_u + \delta_u v_l)\left(1 + K_u \frac{r}{R}\cos\Psi\right) \quad (1)$$

$$v_{il} = (v_l + \delta_l v_u)\left(1 + K_l \frac{r}{R}\cos\Psi\right) \quad (2)$$

$$K_{l,u} = \frac{15\pi}{32}\tan\left(\frac{\chi_{l,u}}{2}\right) \quad (3)$$

$$\chi_{l,u} = tan^{-1}\left(\frac{\mu_{l,u}}{-\lambda_{l,u}}\right) \quad (4)$$

Where v_{iu} and v_{il} are the axial induced velocities on the upper and lower disc planes,K_u and K_l are thefunction of inclination angle of upper and lower rotor wakes, δ_u and δ_l are the flow interaction factors of upper and lower rotors. It is derived from momentum theory in literature [16]. Fig. 1 shows the curve of interaction factors varying with advance ratio.

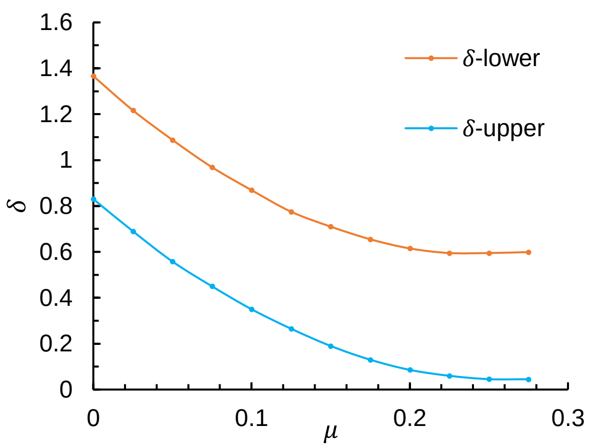


Fig. 1. Interaction factor vs advance ratio

2.2 Rotor Performance Validation of the Blade Element Theory

Falarski [1] investigated the full-scale advancing blade concept rotor system at high advance ratios in 1971. The experiment covers an advance ratio range of 0.2 to 0.9, and a shaft angle range of -10° to 8°, with all the force and moment trimmed. The other parameters of the experiment is shown in table. 1.

Table 1. Rotor Parameters

Parameter	Value
Rotor radius , m	6.098
Blade chord, m	0.5273(root)-0.26365(tip)
Cutout radius, m	0.7391
Rotor solidity	0.111
Precone angle, deg	5(upper), 0(lower)
Airfoil section	NACA 0030- NACA 0006

Positive directions of forces and moments are shown in Fig. 2.

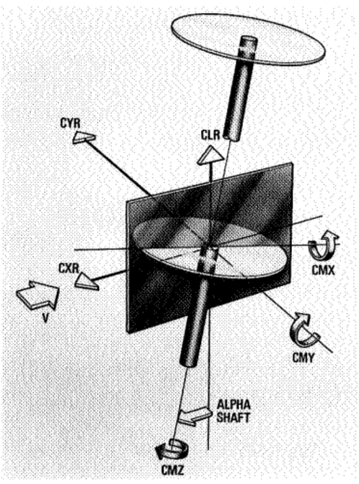


Fig. 2. Sketch of forces and moments

The experimental data of Run 5 was used to validate the BEM. The advance ratio is 0.21, shaft angle is from -10 ° to -4 °.The flow interaction factors are obtained from Fig. 1 and rotor performance predicted by BET are compared with the experimental data in Fig.3. The *x* coordinate PT (point) represents the serial number.

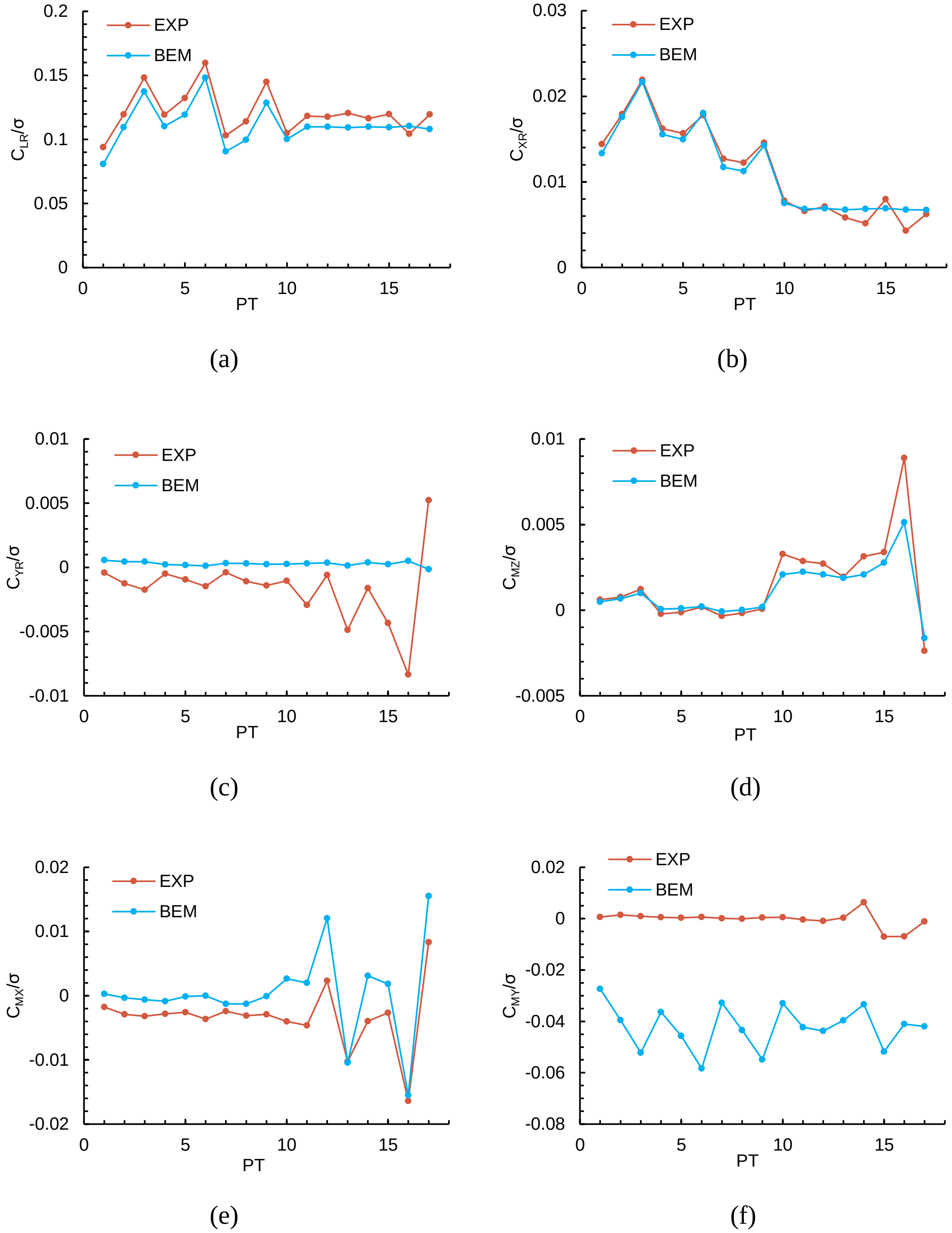


Fig. 3. Result comparison of BEM and experiment

Fig. 3 shows that C_{LR}/σ, C_{XR}/σ, C_{MX}/σ, and C_{MZ}/σ agree well with the experimental result. However, C_{YR}/σ and C_{MY}/σ have a certain disparity with experiment. The reasons are supposed to be: (1) flow interaction of the rotor with faired body in the test, while the body is ignored in the BEM method; (2) The moment coefficients on the helicopter in the experiment are compared with moment coefficients on the rotor in BEM theory; (3) The trimmed result refers to variables with quite small value, which exaggerates the error of BEM results.

2.3 The Trim Method Based on Gradient Optimization Method

It is assumed that the rotating speed of the rotor is constant and the propulsive power is off for the advancing ratio discussed in this paper. Therefore, the control variables include: collective pitch (θ_u , θ_l), cyclic pitch (A_{1u},A_{1l},$B_{1u}B_{1l}$), and shaft angle α. Altogether there are 7 variables. Referring to the unbalanced number between constrains and variables, and considering the lift offset (LO) benefit on ABC rotor in high advancing ratio, the LO value are selected as the additional constraint.

In the BET trim method for the rigid coaxial rotors, the input x contains 7 variables including the shaft angle of attack, shown in Eq. (5). The output F contains 6 constraints, i.e. the force and moment coefficients of the rotor, see Eq. (6).

$$x = [\theta_u, A_{1u}, B_{1u}, \theta_l, A_{1l}, B_{1l}, \alpha] \quad (5)$$

$$F(x) = [C_{LR}, C_{XR}, C_{YR}, C_{MZ}, C_{MY}, C_{MX}]/\sigma \quad (6)$$

In Eq. (6), all the force and moment are in wind axis system. In a steady forward flight, the net force and moment on the helicopter shall be zero. Therefore, the problem changes to find x^* which makes Fequals to:

:

$$F(x^*) = [C_{LR}^*/\sigma, 0, 0, 0, 0, 0] \quad (7)$$

In Eq. (7), $C_{LR}^*$is a lift coefficient to match the gross weight of the helicopter. The trim problem can be transformed to an optimization problem as follows:

$$\min f(x)$$

$$\text{by varying } \mathrm{x} = [x_1, x_2, \dots, x_n] \quad (8)$$

$$f(x) = |F(x) - F^*|$$

One of the gradient optimization methods, Broyden-Fletcher-Goldfarb-Shanno (BFGS) Method, is used to solve the problem. The iteration stops when residual is less than 10^{-4}. Residual is defined as:

$$\text{Residual} = \max\left((\boldsymbol{F} - \boldsymbol{F}^*) \cdot (\boldsymbol{F} - \boldsymbol{F}^*)\right) \quad (9)$$

A typical residual history curve and variable history curve are shown in Fig. (4-5).

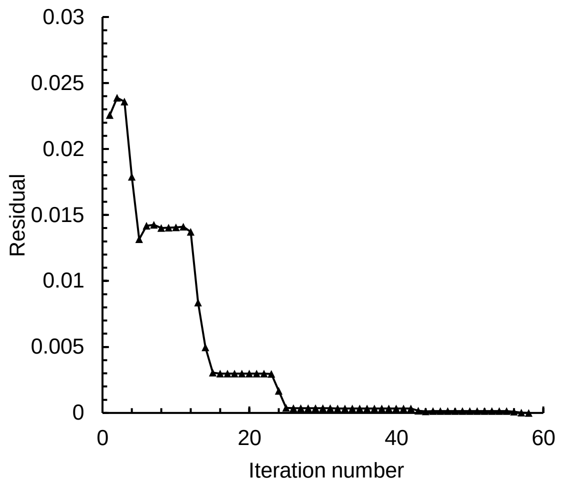


Fig. 4. Residual vs iteration number

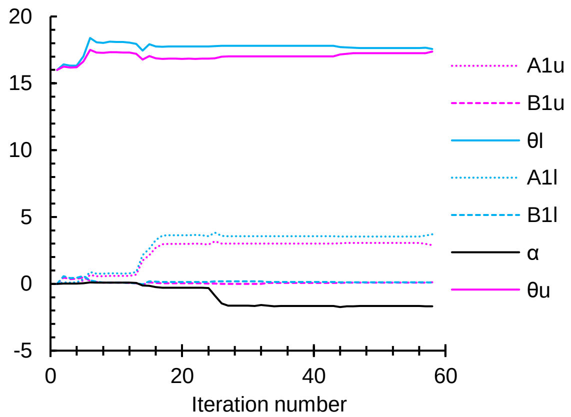


Fig. 5.Variables vs iteration number

3. Performance of XH-59A Rotor in Forward Flight

3.1 Application of Trim Method on XH-59A

The XH-59A is an experimental coaxial compound helicopter developed by Sikorsky Aircraft as the demonstrator of the Advancing

Blade Concept (ABC). The parameters of the XH-59A is shown in table 2.

Table 2. XH-59A Parameters

Parameter	Value
Gross weight, lb	13000
Rotor radius , m	5.486
Blade tip chord, m	0.2743
Blade taper	2:1
Blade twist, deg	-10
Cutout radius, m	1.1
Rotor solidity	0.1267
Precone angle, deg	3
Airfoil section	NACA series

Positive directions of forces and moments are shown in Fig. 6.

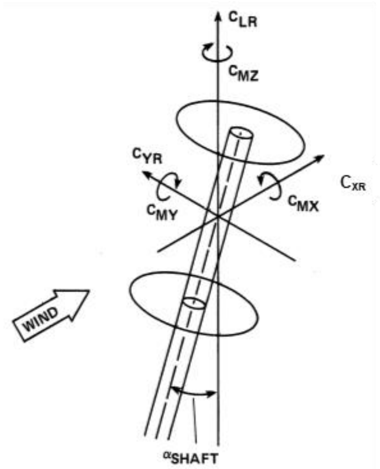


Fig. 6. Sketch of forces and moments

As a helicopter, the XH-59A demonstrated a maximum level speed of 156 knots (289 km/h), In this paper, the rotor rotating speed is 320RPM, the range of advancing ratio is 0.07~0.4, referring to an air speed range of 25~141.67knots. The maximum tip Mach number is 0.73, below the critical Mach number 0.85. In the steady forward flight condition, the lift produced by the rotor can be considered equal to the weight of helicopter approximately (13000lb). Therefore, the C_{LR}/σ is set to 0.1286. The drag of the fuselage is ignored, and the auxiliary propulsion is off. The target C_{XR} is zero because that the drag of the rotor is balanced by the horizontal component of the rotor thrust.

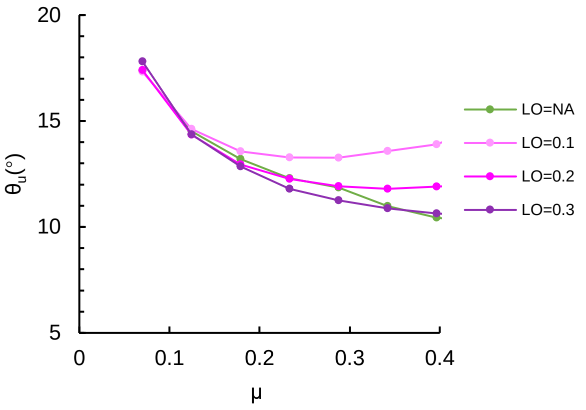
The XH-59A rotor consists of two rigid, contra-rotating rotors, which belongs to the advancing blades concept (ABC). To represent this feature, Lift Offset (LO) is defined in Eq. (10).

$$\mathrm{LO} = \frac{|C_{MX}^{u}| + |C_{MX}^{l}|}{C_{LR}^{u} + C_{LR}^{l}} \qquad (10)$$

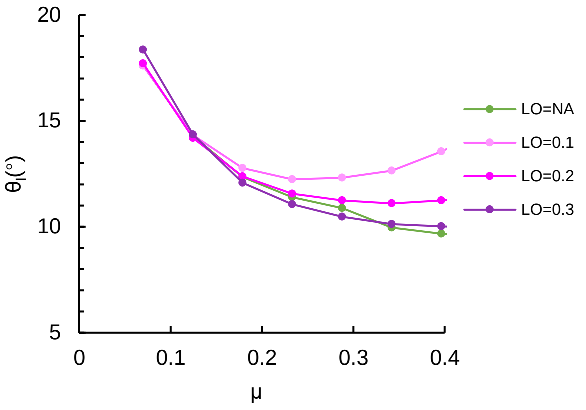
To evacuate the influence of LO, four groups are compared. In the first group, LO is not a target constraint. While in the other three groups, LO is assigned 0.1, 0.2 and 0.3 respectively. That is, the constant value of LO is added in trim target, shown in Eq. (11). To validate the flight test data, assumptions are proposed as follows: (1) The fuselage is ignored in the trim method; (2) The fuselage pitch angle is zero; (3) The auxiliary propulsion is off under level flight speed 156knots (advancing ratio 0.41). With these assumptions, the drag force on the rotor can represent the drag force of the helicopter, which is balanced by the rotor thrust components on the upwind direction, therefore, C_{XR} is 0 in Eq. (11). Hence, the final target constraints are:

$$F(x^{*}) = [0.1286, 0, 0, 0, 0, 0, (LO)] \qquad (11)$$

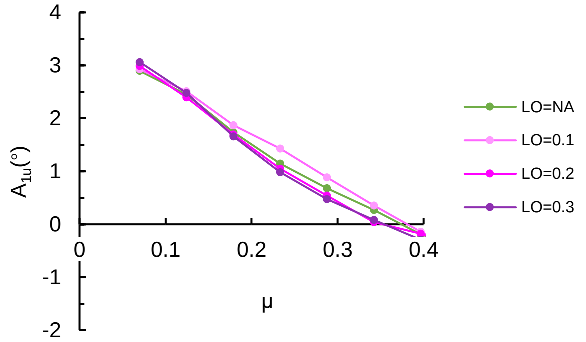
And the variables selected are the same as Eq. (5).The initial x is [16, 0, 0, 0, 0, 0, 0]. After the iteration, the trimmed result is shown in Fig. 7.


θu(°)
μ
LO=NA
LO=0.1
LO=0.2
LO=0.3

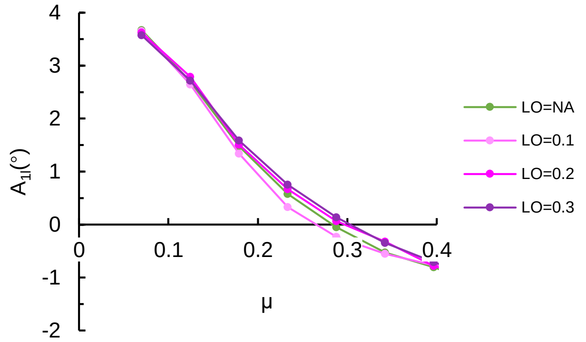
(a)


θl(°)
μ
LO=NA
LO=0.1
LO=0.2
LO=0.3

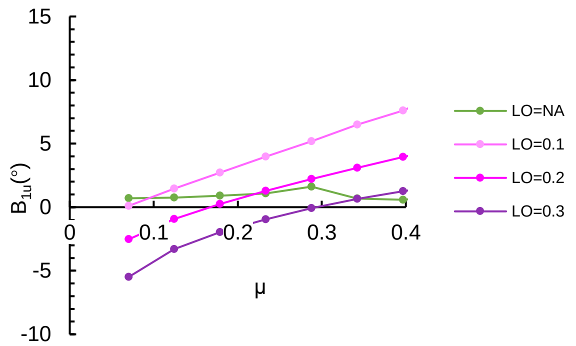
(b)


A1u(°)
μ
LO=NA
LO=0.1
LO=0.2
LO=0.3

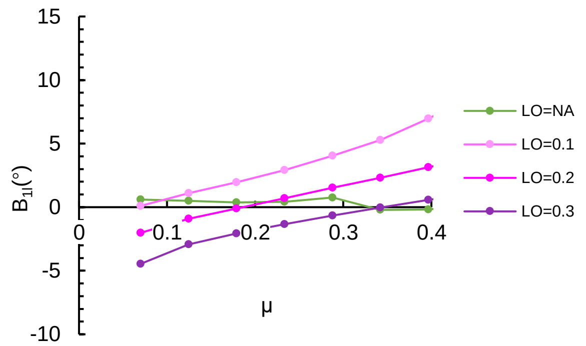
(c)


A1l(°)
μ
LO=NA
LO=0.1
LO=0.2
LO=0.3

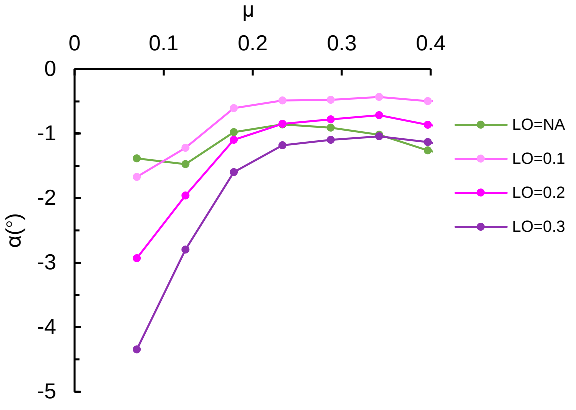
(d)


B1u(°)
μ
LO=NA
LO=0.1
LO=0.2
LO=0.3

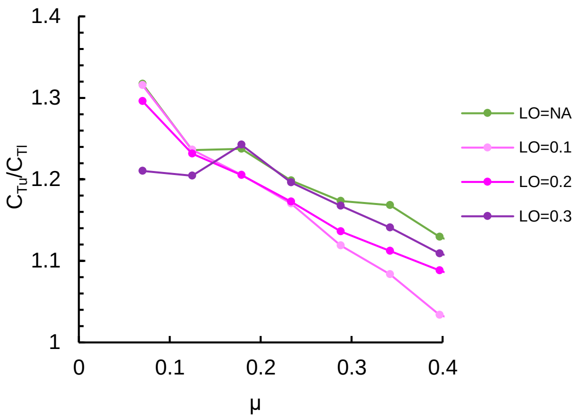
(e)


B1l(°)
μ
LO=NA
LO=0.1
LO=0.2
LO=0.3

(f)



(g)



(h)

Fig. 7. The Trimmed result

Fig.7 (a) and (b) show that the collective pitch range of upper and lower rotor is 10°~18°. Except for LO=0.1, the collective pitch decreases with advancing ratio. The decreases of collective pitch slow down when μ>0.2. When μ<0.2, the influence of LO value on the collective pitch is quite small. At same advancing ratio, the increase of LO results in the decrease of collective pitch, especially in high advance ratio. This feature means a larger LO can benefit the helicopter a lower required power in high speed forward flight without consideration of the other variables.

Fig. 7(c) and (d) show that the longitude cyclic pitch decreases with advancing ratio. LO has a little influence on longitudinal pitch.

Fig. 7 (e) and (f) show that for the unrestricted LO, the lateral pitches are nearly constants. While for the constant value of LO, the lateral pitch increases with advancing ratio. At the same advancing ratio, the bigger the LO value, the smaller the lateral pitch. This tend can be easily explained by BEM theory. It is well accepted that the increase of the lateral pitch contributes to a decrease of roll moment for single rotor, so when the advance ratio increases in Fig. 7 (e) and (f), the lateral pitch has to increase to keep the LO constant.

Fig. 7 (g) shows the shaft angle varying with advancing ratio. As can be seen, for the unrestricted LO, the shaft angle is between 1.5°~1°. At low advancing ratio around 0.1, a high value of LO leads to a small shaft angle of attack. While the angle of attack are approximately constant during μ=0.2~0.4 for the three LO groups.

Fig. 7(h) demonstrates the thrust ratio of upper rotor to lower rotor varying with advancing ratio. In the range 0.07≤μ≤0.4, the thrust ratio is 1.01~1.32. The thrust ratio decreases with advancing ratio. The result agrees with the statistical data in literature [18] approximately. Chen summarized that under torque balance situation, the thrust ratio of upper rotor to lower rotor is about 1.18 for hover and 1.05 when advancing ratio is greater than 1.5 in forward flight.

The value of LO in the first group is plotted in Fig. 8. It shows that LO increases with advancing ratio. LO is in the range 0.08~0.33. The result is reasonable that a suitable LO value is beneficial to high advancing ratio situation.

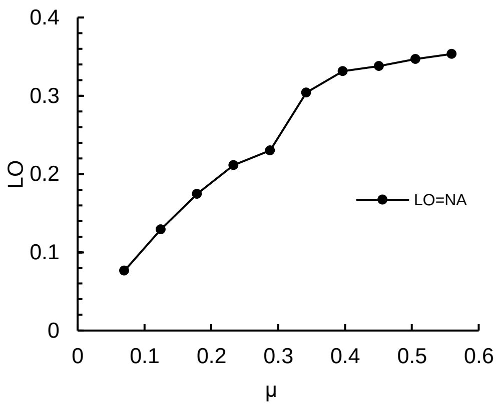


Fig. 8. The value of LO in group 1

3.2 Results Comparison with Flight Test

Finally, the trimmed result are compared with flight test data in literature [8]. In the flight test, the lift to drag ratio (L/D) of the XH-59A helicopter and rotor power are plotted varying with air speed.

In the trim model, the fuselage is ignored. Therefore, the drag of the helicopter can be replaced by the drag of the rotor in addition to the nominal drag of the rotor power, shown in equation (12). The lift to drag ratio is compared in Fig. 9.

$$\text{drag} = \text{rotor drag} + \frac{P}{V} \qquad (12)$$

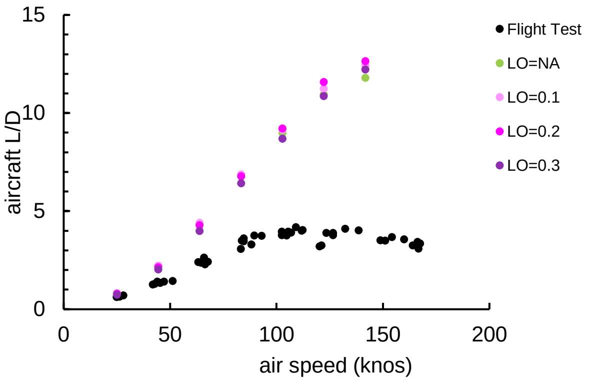


Fig. 9. The lift to drag ratio of XH-59A in forward flight

Fig. 9 shows that the lift to drag ratio of the trimmed model is 1~3 times of the flight test data. The ratio increases with the airspeed in range 25~142 knots for the trim model. Because the fuselage drag is ignored in the trimmed model. According to the power breakdown Fig. for forward level flight in literature [19], the parasite drag and miscellaneous drag are ignored in the trimmed model, while the first one is proportional to V^3 and contributes 1/2 total drag when V>130knots approximately. Therefore, it is reasonable that the predicted lift to drag ratio is 3 times of the flight test in high velocity.

To compare the power of the rotor, a correctional power is introduced in Eq. (13) for the trimmed model, the correction is referred to literature [2]. The correct C_{PRC} is used to calculate the rotor power in Fig. 10.

$$C_{PRC} = C_{PR} + \mu C_{DR} \qquad (13)$$

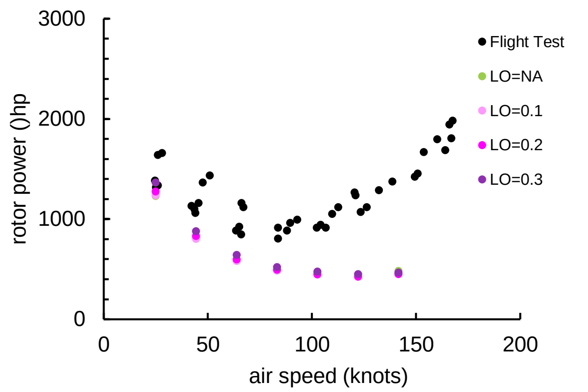


Fig. 10. The XH-59A rotor power in forward flight

Fig. 10 shows that the rotor power of the trimmed model decreases with air speed until 100 knots and then remains to be constant till 142 knots for the trimmed model. The power variation tendency of the trimmed model agree with the profile power trend in literature [19]. While the power of the flight test decrease until 100 knots and then increases. The difference is regarded due to the three assumptions in section 3.1. The existence of fuselage and its pitch angle makes the real power is bigger than the trimmed model.

4 Conclusion

An efficient trim approach based on the BET method for the coaxial rotor in forward flight is developed in this paper.

(1). The accuracy of BET method is validated by wind tunnel test of a rigid coaxial rotor.

(2). In the trim method, the shaft angle of attack and lift offset value are involved as control variables. The gradient optimization method is applied to solve the 7 variables and 6-7 constrains problem.

(3). Assumptions are proposed for the model of XH-59A rotor. Trimmed results of XH-59A rotor in advancing ratio 0.07~0.4 are compared with flight test data and the detailed parameters change are explored.

Acknowledgments

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