The Effects of Cyclic Pitch Control on the Aerodynamic Characteristics of Main Rotors for ABC Helicopters

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ABSTRACT

A new trim method for the multi-control solutions of ABC rotor propeller-augmented compound helicopters is presented and combined with the free-wake method. On the basis of the methods, a comprehensive model for analysing the aerodynamic characteristics of ABC helicopters is furthermore established in this paper. By the developed model, the effects of main rotor’s cyclic pitch control on its aerodynamics are investigated in details. The new trim method does not need to force the same cyclic pitch control to be applied on both upper and lower main rotors as done in other previous analyses, and the numerical examples show that it is reliable and effective in finding a trim state at specified flight condition and getting corresponding control input. Also, the way to weaken the vibration level of the coaxial main rotors of an ABC helicopter by applying different control strategies to two main rotors is preliminarily studied. The calculated results indicate that the oscillation phase displacement created by the different control strategies of two main rotors will make the vibration level of the coaxial main rotors weakened.

INTRODUCTION

Compared with fixed wing aircrafts, helicopters have a drawback of lower cruise speed. In order to overcome the disadvantage, for decades, the researches on new configurations of high-speed helicopters have been made. The Advancing Blade Concept(ABC) rotor[1,2] propeller-augmented compound helicopter[3,4] (also called ABC helicopters) is one of the most successful configurations, in which the X-2 helicopter is a representative one. X-2 helicopter maintains and develops the technical features of conventional helicopters[2], implying an important development direction for future helicopters. However, the helicopter will encounter much more complicated interactional aerodynamics caused by its special configuration.

The ABC helicopter has a popular configuration of coaxial main rotors with a propeller rotor. For the conventional coaxial helicopters, lots of theoretical and experimental investigations were carried out previously, and the vortex theory[5,6] and CFD method[7,8] were often used as the theoretical analytical tools. Nevertheless, when a propeller rotor is compounded into a conventional coaxial helicopter, the interactional aerodynamics of an ABC helicopter will be greatly changed and the previous analytical tools could not be directly applied to the new configuration. On the other hand, the theoretical studies on the ABC rotor propeller-augmented compound helicopter, especially being capable of analysing the interactional
aerodynamic characteristics among the main aerodynamic components, have hardly been found in current publication so far. Until 2008, Kim et al. [9] have built a comprehensive model for analysing the interactional aerodynamics of ABC helicopters firstly. In their model, the VTM method [10] which is actually a kind of viscous vortex one was used. Kim et al comprehensively analysed the aerodynamic characteristics of the main rotors, horizontal tail plane and propeller rotor at different forward-flight conditions. However, because of the VTM method’s application, they had to suffer a huge amount of computations [11], which consequently led to a simplified helicopter trim model carried out in their method [12]. In the simplified trim model, the same cyclic pitch controls were inputted to both the upper and the lower main rotors [9,13,14].

In fact, the trim analysis is important for aerodynamic calculations of the ABC helicopter. In addition, as pointed out by Burgess [15], the lateral lift offset control of the main rotors is the essence of the ABC concept, which means that, for a ABC-rotor propeller-augmented compound helicopter, there are multi-trimmed control solutions at each flight condition, and optimization of performance, rotor moments and vibration are readily affected by use of differential cyclic and collective pitch. Then, this kind of control technique apparently has great value of research [15-17], and the technique could not be achieved by applying simplified trim method with single-control solution for each flight condition. Therefore, the set-up of a trim model, which can get multi-control solutions for each flight condition, is significant, however challenging.

Based on the work of Kim et al, a new comprehensive model for analysing the aerodynamic characteristics of ABC helicopters is developed by combining a free-wake code with a new multi-control-solution trim method. By the developed model, the effects of cyclic pitch control on the aerodynamic characteristics of main rotors for an ABC helicopter are studied, and some new conclusions have been drawn out.

MODEL AND METHODOLOGY

Computational Model

Because of the lack of detailed data in publication of the main rotors of X-2 high-speed helicopter, the calculation model of ABC-rotor propeller-augmented compound helicopter applied in this paper is partially simplified from the data of XH-59A and X-2 helicopters in order to fit the free-wake method. The calculation model is schematically shown in Fig. 1.

As shown in Fig. 1, configuration of the calculation model is similar to X-2, i.e. a generic helicopter configuration that comprises a stiffened twin coaxial rotor system together with an auxiliary tail propeller and a horizontal tailplane. The horizontal tailplane is untwisted and has a rectangular planform (3.74m*0.94m). Its airfoil section is NACA0012. The main rotor system modeled in this study contains two counter-rotating three-bladed rotors, which are separated axially. The blades of both rotors are tapered linearly in planform and have -10° of linear twist and 5.5m of rotor radius. The twin rotors of the coaxial system are arranged so that the
lower rotor rotates anticlockwise and the upper one rotates clockwise when viewed from above. The rotors have been arranged to overlap when blades from both the upper and the lower rotors pass directly over the centreline of the rear fuselage. For simplicity, a constant airfoil section, NACA0012, is used along the entire span of the rotor blades. The geometric properties of the main rotor system are summarized in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Main rotor and propulsor geometries</th>
<th>Main rotor</th>
<th>Propulsor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor radius (m)</td>
<td>5.5</td>
<td>1.54</td>
</tr>
<tr>
<td>Number of rotors</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Blades per rotor</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Root cutout</td>
<td>0.12</td>
<td>0.2</td>
</tr>
<tr>
<td>Twist (°)</td>
<td>-10</td>
<td>-30</td>
</tr>
<tr>
<td>Tip Chord (m)</td>
<td>0.554</td>
<td>0.2772</td>
</tr>
<tr>
<td>Taper</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Airfoil sections</td>
<td>NACA0012</td>
<td>NACA0012</td>
</tr>
</tbody>
</table>

In addition, a five-bladed propeller is used to represent an auxiliary thrust-producing device mounted in pusher configuration to the rear of the fuselage. The blades of this propulsor feature a tapered root end, -30° of linear twist, and a NACA0012 sectional profile. Its rotational speed is fixed at 4 times the main rotor speed and its direction of rotation is anticlockwise when seen from the rear of the aircraft. A summary of the geometry of the propulsor is given in Table 1.

Free-wake method

In this paper, the rotor wake is calculated by the time-marching free-wake method\cite{18}, which divides the wake filament into lots of straight vortex segments. Each segment moves with the local velocity, whose governing equation can be given as

$$\frac{dr}{dt} = v(r,t)$$

where \(r\) represents the position vector of the vortex node, and \(v\) is the local velocity.

To any node along the rotor wake filament, the 4th-order accurate Adams-Bashforth-Moulton predictor-corrector scheme\cite{19} is applied, which is

**Predictor:**

$$r_{t+4\Delta t}^* = r_{t+3\Delta t} + \frac{h}{24}(55v_{t+3\Delta t} - 59v_{t+2\Delta t} + 37v_{t+\Delta t} - 9v_t)$$

**Corrector:**

$$r_{t+4\Delta t} = r_{t+3\Delta t} + \frac{h}{24}(9v_{t+4\Delta t} + 19v_{t+3\Delta t} - 5v_{t+2\Delta t} + v_{t+\Delta t})$$

where the predictor of the explicit 4th-order accurate Adams-Bashforth method will firstly give a predicted solution \(r_{t+4\Delta t}^*\), then the corrector of the implicit one will obtain the final solution \(r_{t+4\Delta t}\). The verification of the reliability of this predictor-corrector scheme can be found in other references, which therefore will not be given here again.

**Trim Methodology**

During the flight of a helicopter, pilots change the flight condition and the aerodynamic force by controlling the rotor inputs. Therefore, to obtain the accurate control data, a proper trim model should be contained in the analysis of interactional aerodynamic characteristics of a helicopter. As mentioned before, within the few studies of interactional aerodynamic characteristics of ABC helicopters, because of the huge amount of computations, a simplified helicopter trim model was carried out in their method. In their simplified trim model, same cyclic pitch control was inputted to both the upper and the lower main rotors\cite{9}. On the other hand, in the current study, a more complicated trim methodology is presented instead of the former simplified one.

Specifically, different from the trim model of an isolated rotor, for an ABC helicopter, there are more control input quantities. Seven important ones of them are picked up, which are the collective pitch and cyclic pitch of the lower rotor, \(A_{0L}, A_{1L}\) and \(A_{2L}\),...
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collective pitch and cyclic pitch of the upper rotor, $A_{0L}$, $A_{1L}$ and $A_{2L}$, collective pitch of propulsive rotor, $A_{0P}$. Then the control input vector of an ABC helicopter can be given as

$$z = (A_{0L}, A_{1L}, A_{2L}, A_{0U}, A_{1U}, A_{2U}, A_{0P})^T$$

(3)

Where the blade pitch of main rotors can be defined by azimuth angle $\psi$ as

$$\theta_i(\psi) = A_0 + A_1 \cdot \cos(\psi) + A_2 \cdot \sin(\psi)$$

(4)

As shown in Fig. 1, the xyz-coordinate system is adopted. The Cartesian components of the overall forces and moments constitute the trim state vector, i.e.

$$y = (F_x, F_y, F_z, M_x, M_y, M_z)^T$$

(5)

In order to match the number of control input variables with that of the trim ones, the lateral force, $F_y$, will be ignored, which is much weaker than the other forces. And the cyclic pitch inputs of the upper rotor, $A_{1U}$ and $A_{2U}$, will be used as the default values, which do not change during the trim process. In such way, failure of solving trim equation could be avoided. Therefore, both the control input and the trim state quantity consist of 5 components. They can be regiven as follows

$$\Sigma = (A_{0L}, A_{1L}, A_{2L}, A_{0U}, A_{0P})^T$$

(6)

$$\Psi = (F_x, F_y, F_z, M_y, M_z)^T$$

(7)

It should be pointed out, the default values, $A_{1U}$ and $A_{2U}$, need to be chosen carefully, which means that improper values will lead to the failure of solving the trim equation. So, the trim equation can be given as

$$\Delta \Sigma = \lambda J^{-1} \Delta \Psi$$

(8)

Where $J$ is the Jacobean matrix, and $\lambda (0 < \lambda \leq 1)$ is a relaxation factor used to maintain the numerical stability. To verify the reliability of this trim methodology, the flight condition at advance ratio of 0.15 is chosen as a numerical example. Fig. 2 gives convergence process of the control input and trim variables. As shown in Fig. 2 (a), all the five trim state data have convergented from various initial values to zero. On the other hand, as shown in Fig. 2 (b), all the five control input data have convergented to some specific values accordingly. It can be seen from this trim procedure that the trim methodology presented in this paper is reliable and effective in finding a trim state under specified flight conditions and getting corresponding control input data. Moreover, different from the conventional simplified trim method, by assigning different default values, $A_{1U}$ and $A_{2U}$, present trim methodology can find much more trim states under one specified flight condition to investigate the interactional aerodynamic characteristics of ABC helicopters more deeply.

![Fig. 2 Convergence process of the control input and trim variables ($\mu = 0.15$)](image-url)
RESULTS AND ANALYSES

Table 2 presents 8 different trim states at the same flight condition of $\mu = 0.3$. As pointed out before, the lateral lift offset control of the main rotors is achieved by assigning the default values, $A_{1U}$ and $A_{2U}$.

Table 2  Control input data of different trim states ($\mu = 0.3$)

<table>
<thead>
<tr>
<th>Trim state</th>
<th>$A_{0L}$</th>
<th>$A_{0U}$</th>
<th>$A_{1L}$</th>
<th>$A_{1U}$ (Default)</th>
<th>$A_{2L}$</th>
<th>$A_{2U}$ (Default)</th>
<th>$A_{0F}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trim state 1</td>
<td>0.07336</td>
<td>0.07387</td>
<td>0.03647</td>
<td>0.04</td>
<td>0.00366</td>
<td>0</td>
<td>0.44455</td>
</tr>
<tr>
<td>Trim state 2</td>
<td>0.10524</td>
<td>0.10477</td>
<td>0.03545</td>
<td>0.04</td>
<td>-0.05821</td>
<td>-0.06</td>
<td>0.4309</td>
</tr>
<tr>
<td>Trim state 3</td>
<td>0.15602</td>
<td>0.16084</td>
<td>0.0493</td>
<td>0.04</td>
<td>-0.14298</td>
<td>-0.15</td>
<td>0.41474</td>
</tr>
<tr>
<td>Trim state 4</td>
<td>0.23973</td>
<td>0.24515</td>
<td>0.08195</td>
<td>0.08</td>
<td>-0.23921</td>
<td>-0.25</td>
<td>0.39867</td>
</tr>
<tr>
<td>Trim state 5</td>
<td>0.04457</td>
<td>0.04479</td>
<td>0.05354</td>
<td>0.055</td>
<td>0.08852</td>
<td>0.08</td>
<td>0.48077</td>
</tr>
<tr>
<td>Trim state 6</td>
<td>-0.00484</td>
<td>0.09013</td>
<td>0.12977</td>
<td>0.01</td>
<td>0.16728</td>
<td>0.08</td>
<td>0.55107</td>
</tr>
<tr>
<td>Trim state 7</td>
<td>0.09298</td>
<td>5.83E-5</td>
<td>-0.00892</td>
<td>0.15</td>
<td>0.0889</td>
<td>0.15</td>
<td>0.5527</td>
</tr>
<tr>
<td>Trim state 8</td>
<td>0.04481</td>
<td>0.03261</td>
<td>0.05091</td>
<td>0.08</td>
<td>0.11962</td>
<td>0.12</td>
<td>0.52316</td>
</tr>
</tbody>
</table>

All the 8 trim states can be approximately divided into two groups. As shown in Table 2, trim states 1~5 belong to one group, where the cyclic pitch of the upper and the lower main rotors is very close. It means $A_{1L} \approx A_{1U}$, and $A_{2L} \approx A_{2U}$  (9)

In this group, Fig. 4, Fig. 6, Fig. 8, Fig. 10 and Fig. 12 show the distributions of blade loading over the coaxial main rotors respectively, where darker area represents higher loading. As shown in these figures, in all the five trim states, distributions of blade loading over the upper and the lower rotors are approximatively mirror-symmetrical. Fig. 3 (a), Fig. 5 (a), Fig. 7 (a), Fig. 9 (a) and Fig. 11 (a) give their temporal variations in the thrust produced by the coaxial main rotors respectively. It can be seen, because of the mirror symmetry of main rotor loading distributions, the oscillation phases of the thrust of the upper and lower rotors are almost identical, i.e. the wave peaks meet together and the wave valleys also coincide. This oscillation feature may aggravate the vibration level of the coaxial main rotors.

On the other hand, Fig. 3 (a), Fig. 5 (a), Fig. 7 (a), Fig. 9 (a) and Fig. 11 (a) respectively show their temporal variations in the power consumption of the coaxial main rotors. Obviously, the same oscillation characteristics are also found.

Fig. 3  Trim state 1, temporal variation in the thrust and power of the upper and lower rotors of the coaxial system over one revolution at $\mu = 0.3$
Fig. 4  Trim state 1, distribution of blade loading over the coaxial main rotors at $\mu = 0.3$.

Fig. 5  Trim state 2, temporal variation in the thrust and power of the upper and lower rotors over one revolution at $\mu = 0.3$.

Fig. 6  Trim state 2, distribution of blade loading over the coaxial main rotors at $\mu = 0.3$.

Fig. 7  Trim state 3, temporal variation in the thrust power of the upper and lower rotors over one revolution at $\mu = 0.3$.

Fig. 8  Trim state 3, distribution of blade loading over the coaxial main rotors at $\mu = 0.3$. 

(a) Lower main rotor  (b) Upper main rotor
The above results directly relate to the lateral cyclic pitch coefficient of main rotors, $A_2$ (Table 2). Specifically, for trim state 1, $A_2$ values of both main rotors are around 0, i.e. there is no extra lateral cyclic control on the upper and lower rotors. Therefore trim state 1 can be considered as a benchmark of
all the 8 states. At this state, as shown in Fig. 4, the loading centres of the upper and lower rotors are both distributed at the advancing blade side partial to the rear side on the rotor disc. The loading distributions are very concentrated. Therefore, vibration levels of thrust of main rotors are relatively low in trim state 1 among the first group (see Fig. 13).

At trim state 2, $A2$ values of two main rotors are around -0.06, which means that there is a little extra negative lateral cyclic control on the upper and lower rotors. Consequently, as shown in Fig. 6, the loading centres move towards the rear side on the rotor disc, and the loading distributions are not as concentrated as that in trim state 1. Then trim state 2 shows a little higher vibration level of thrust of main rotors than that of state 1 (see Fig. 13). Similarly, at trim state 3, $A2$ values of two main rotors are around -0.15. More extra negative lateral cyclic control on the upper and lower rotors makes their loading centres move towards the rear side on the rotor disc, see Fig. 8. As a result, the loading distributions disperse further and the darkest region becomes unclear. Then, as shown in Fig. 13, the vibration levels of thrust of main rotors at this state get higher than the former ones.

At trim state 4, $A2$ values of two main rotors are around -0.25, which means that there is a large negative lateral cyclic control on the upper and lower rotors. Consequently, as shown in Fig. 10, the loading centres move further towards the rear side on the rotor disc, and the loading distributions are very disordered. So trim state 4 presents the highest vibration level of thrust of main rotors, see Fig. 13.

At trim state 5, $A2$ values of two main rotors are given as 0.08, which means that there is an extra positive lateral cyclic control on the upper and lower rotors. Different from the former trim states, as shown in Fig. 12, at this state, the loading centres move towards the advancing blade side on the rotor disc, and the loading distributions are also very concentrated. Therefore, vibration levels of thrust of main rotors are relatively low at trim state 5 among the first group, see Fig. 13.

For the other group, containing trim states 6~8, in which the cyclic pitch controls between the upper and lower rotors are set to be different, see Table 2, i.e.

\[ A1_L \neq A1_U \quad \text{or} \quad A2_L \neq A2_U \quad (10) \]

In this group, Fig. 15, Fig. 17 and Fig. 19 show the distributions of blade loading over the coaxial main rotors respectively, where darker area represents higher force. As shown in the figures, because of the different control strategies of two main rotors being applied, distributions of blade loading over the upper and lower rotors are no longer mirror symmetrical as shown previously in the first group, but asymmetry, especially the loading centres (black regions in figures). Furthermore, Fig. 14 (a), Fig. 16 (a) and Fig. 18 (a) give their temporal variations in the thrust produced by the coaxial main rotors respectively. Obviously, there are oscillation phase displacement created by the different control strategies of two main rotors, and wave peaks meet with wave valleys here. Therefore, different from the results in the first group, this special oscillation characteristic in the second group may weaken the vibration level of the coaxial main rotors, which is beneficial for a high-speed helicopter.
Fig. 14  Trim state 6, temporal variation in the thrust and power of the upper and lower rotors over one revolution at $\mu =0.3$

Fig. 15  Trim state 6, distribution of blade loading over the coaxial main rotors at $\mu =0.3$

Fig. 16  Trim state 7, temporal variation in the thrust and power of the upper and lower rotors over one revolution at $\mu =0.3$

Fig. 17  Trim state 7, distribution of blade loading over the coaxial main rotors at $\mu =0.3$

Fig. 18  Trim state 8, temporal variation in the thrust and power of the upper and lower rotors over one revolution at $\mu =0.3$
As shown in Fig. 13, the vibration levels of the coaxial main rotors in the second group with appropriate different control strategies of two main rotors are all below the ones in the first group with the same control strategies of two main rotors. The results confirm the possibility of weakening the vibration level of the coaxial main rotors by applying proper control strategies to the main rotors, therefore to enhance the performance in high-speed flight.

CONCLUSIONS

(1) The numerical example shows that the trim method presented in this paper is reliable and effective in finding a trim state at a specified flight condition and getting corresponding control inputs. Different from the simplified trim method as used in previous work, the current trim method can find multi-solution trim states at a specified flight condition, which is more suitable for investigating the lateral lift offset control of ABC helicopters.

(2) At a forward-flight condition, when the same control strategies are used for two main rotors, if the lift centre is located on the retreating side of rotor disk, then the higher vibration levels will occur on the rotor blades, and the efficiency of the main rotor will be reduced.

(3) The results show that it is possible to reduce the vibration level of the coaxial main rotors by applying different control strategies to the two main rotors respectively. The oscillation phase displacement created by the different control strategies of two main rotors will weaken the total vibration level of the coaxial main rotors of ABC helicopters.

REFERENCES


